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MATHEMATICAL MODEL OF SEWAGE SLUDGE FLUIDIZED BED INCINERATOR CAPACITIES AND COSTS

G. J. Ducar, et al

General American Transportation Corporation
Niles, Illinois

September 1969

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MATHEMATICAL MODEL OF SEWAGE SLUDGE FLUIDIZED BED INCINERATOR CAPACITIES AND COSTS

ADVANCED WASTE TREATMENT RESEARCH LABORATORY-X

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27 Abstract

The development of a computer program to evalute sewage sludge fluidized bed incineration systems is described. Data for the program was collected from manufacturers, a literature survey and field trips to operating installations. Most of the data was obtained from the field because of the lack of available information from the other sources. More than fifty correlation relationships were attempted before the necessary data could be reasonably represented. Equations were developed for the least square curves which fitted the data best. These equations were used as the basis for the computer program developed to size some of the major components and to estimate capital, operating and maintenance costs for the fluidized bed incineration system.

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MATHEMATICAL MODEL OF SEWAGE SLUDGE FLUIDIZED BED INCINERATOR CAPACITIES AND COSTS

by

G. J. Ducar and P. Levin

for

The Advanced Waste Treatment Research Laboratory
Robert A. Taft Water Research Center

This report is submitted in fulfillment of Contract No. 14-12-415 between the Federal Water Pollution Control Administration and General American Transportation Corporation.

U. S. Department of the Interior
Federal Water Pollution Control Administration
Cincinnati, Ohio

September, 1969

FOREWORD

In its assigned function as the Nation's principal natural resource agency, the United States Department of the Interior bears a special obligation to ensure that our expendable resources are conserved, that renewable resources are managed to produce optimum yields, and that all resources contribute their full measure to the progress, prosperity, and security of America -- now and in the future.

This series of reports has been established to present the results of intramural and contract research studies carried out under the guidance of the technical staff of the FWPCA Robert A. Taft Water Research Center for the purpose of developing new or improved wastewater treatment methods. Included is work conducted under cooperative and contractual agreements with Federal, state, and local agencies, research institutions, and industrial organizations. The reports are published essentially as submitted by the investigators. The ideas and conclusions presented are, therefore, those of the investigators and not necessarily those of the FWPCA.

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ABSTRACT

This report describes the development of a computer program to evalute sewage sludge fluidized bed incineration systems. Data for the program was collected from manufacturers, a literature survey and field trips to operating installations. Most of the data was obtained from the field because of the lack of available information from the other sources.

More than fifty correlation relationships were attempted before the necessary data could be reasonably represented. Equations were developed for the least square curves which fitted the data best. These equations were used as the basis for the computer program developed to size some of the major components and to estimate capital, operating and maintenance costs for the fluidized bed incineration system.

INTRODUCTION

Domestic and industrial sewage wastes are mixed with water and piped to a sewage treatment plant. To reclaim and purify the water mixed with the sewage, many processes can be used. When attempts are made to separate the suspended solids from the water (dewatering), only a portion of the separation can be achieved. The resulting effluents from the dewatering device are a stream of turbid water and a stream composed of approximately 70% water and 30% solids by weight (sludge). This sludge must be disposed of in some sanitary way (ultimate disposal).

The cost of the ultimate disposal of solids generated at waste water treatment plants can amount to 25 to 50% of the construction and operating costs of an entire waste treatment plant. Incineration of this sludge reduces the volume of wastes to be disposed of by approximately 90% and produces ash and flue gas. Incineration is often the only method available to dispose of sludge.

A recently developed incineration technique uses a fluidized bed of inert material capable of completely oxidizing all the organic material in the sludge. This technique is based on the principle, long used for processing in the chemical industry, that when solids are suspended in an upward-moving stream of gases, the mixture possesses the characteristics of a liquid. The properties of this fluidized bed in terms of mixing and heat transfer can be utilized to effect both rapid mixing and almost instantaneous incineration of the organic material in sludge.

The purpose of this study was to develop a mathematical model of fluidized bed incinerators for burning sewage sludge. The model was to be composed of equations which represented the incineration equipment and process. Such a model would help FWPCA determine approximate sizing of the principal reaction vessels and associated equipment, the amount of fuel and power required, and estimates of the capital, operating, and maintenance costs for fluidized bed incineration systems to be funded. The necessary equations were developed from data obtained in the literature, and surveys conducted at equipment manufacturers plants and in the field.

It was not possible to obtain itemized cost breakdowns for each of the system components. Therefore, capital costs were developed on a systems basis:

1) The system costs developed in this program include the components of Figure 2.

2) The stream vector required for input to this program is to represent the sludge cake leaving the centrifuge.

DESCRIPTION OF SYSTEMS ANALYZED

Terminology

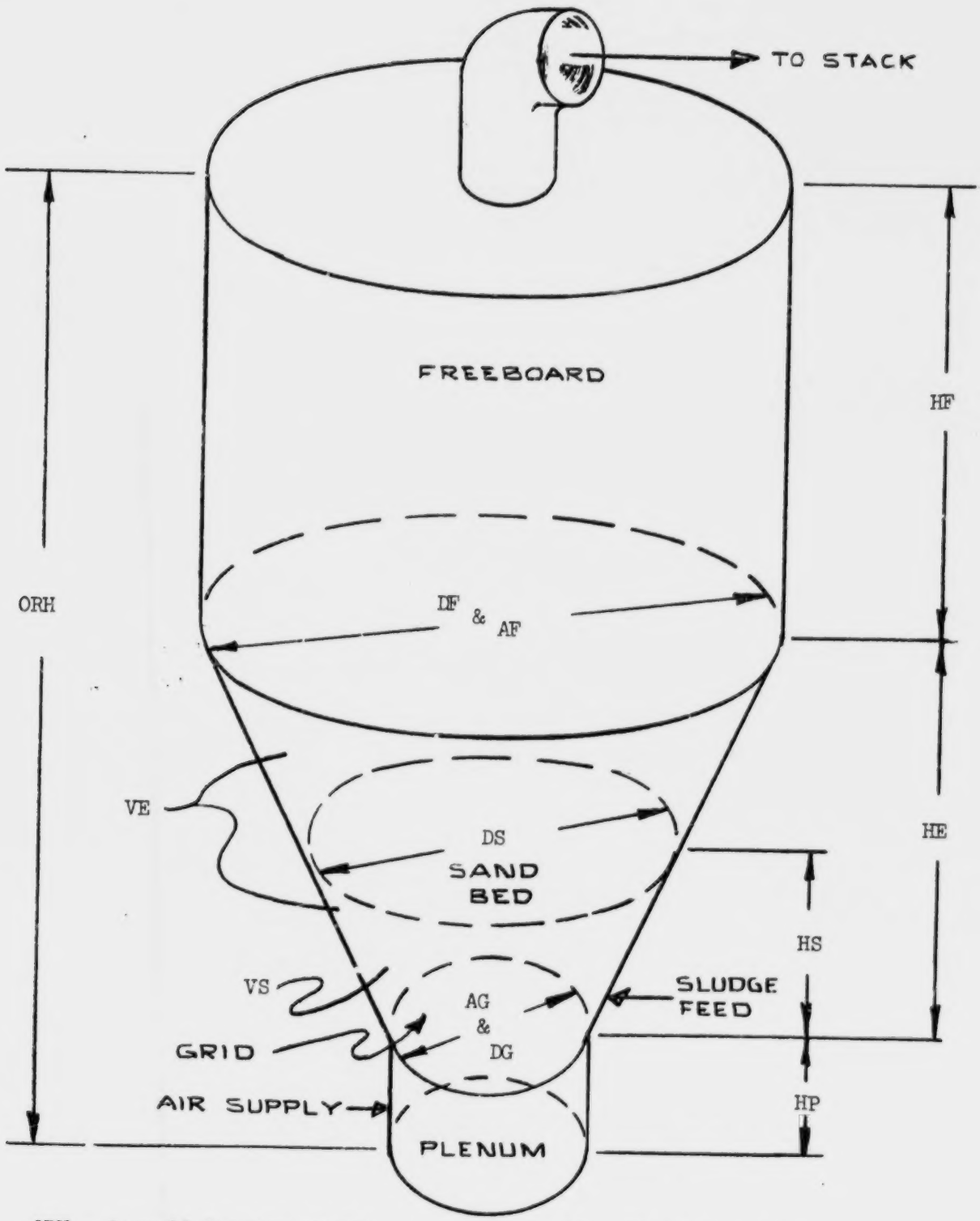
A schematic of the reactor or combustion chamber which is the heart of the fluidized bed incineration system is shown in Figure 1 which illustrates the parameters related directly to the reactor and the various regions of the reactor. The lower section of the reactor consists of an air plenum and a grid for sand support. Above the grid is the sand bed (tapered portion of reactor). When air is blown through the sand, it is fluidized (thus expanding the sand). The section above the expanded sand bed is termed the area free-board. The terminology shown in Figure 1 is specifically related to the reactor vessel. However, this program required a more comprehensive system analysis.

System Components and Operation

The system components included in this study are shown in Figure 2, which illustrates the complete fluidized bed incineration system usually purchased as a package. This system was used as the basis for including equipment in the study because cost data collected included all of the components, as a group, as shown in Figure 2. The waste feed and dewatering system usually consists of centrifuges belt conveyors and a screw feeder at the reactor. Since it was not possible to get costs for the individual components, it was necessary to develop cost information for the total system.

Sludge is dewatered in a centrifuge or vacuum filter. Costs developed for this program are based on systems using a centrifuge. The sludge cake is conveyed directly into the reactor by means of a special screw feeder. Some-times the screw feeder is connected to flexible reinforced ducting through which the sludge is conveyed to the reactor. Air from the blower is passed into a plenum and through a sand-bed supporting grid. This grid also serves to distribute the air so that fairly uniform fluidization of the sand occurs above the grid. The sand bed is maintained at temperatures between 1220° and 1800°F. (The exact maximum and minimum temperatures attainable are determined by the temperature at which essentially complete combustion occurs.) Bed temperature is controlled by fuel regulations, water sprays, and excess air flow. The sludge is burned almost completely in the bed, but because of the mixing characteristics of the fluidized bed, there is considerable burning above the sand bed in some instances. Therefore, in some instances, the above-bed temperature in the freeboard area may be several hundred degrees higher than the bed temperature.

The freeboard serves to keep the sand from being carried out of the reactor with the exhaust products and also serves as a secondary combustion chamber. The exhaust products leave the freeboard section and pass through an air preheater (if one is used). The gases are then cooled to approximately 160°F by a water spray before entering the scrubber where the fly ash and small sand particles, carried out of the reactor with the flue gas, are removed from the gas stream.



ORH - Overall Reactor Height
VE - Volume Expanded
VS - Volume Static
DF - Diameter Freeboard
AF - Area Freeboard

DS - Diameter Static
HS - Height Static
AG - Area Grid
DG - Diameter Grid
HP - Height Plenum
HE - Height Expanded

Figure 1 REACTOR TERMINOLOGY

The warmup burner, shown at the side of the freeboard in Figure 2, is used to preheat the reactor to 1000°F before the bed burners are ignited. Alternatively, the preheat burner may be located in the plenum to preheat the incoming combustion air. The warmup burner is usually extinguished when the bed burners are ignited.

The air supply is controlled so that approximately 4% O_2 is present in the exhaust gases.

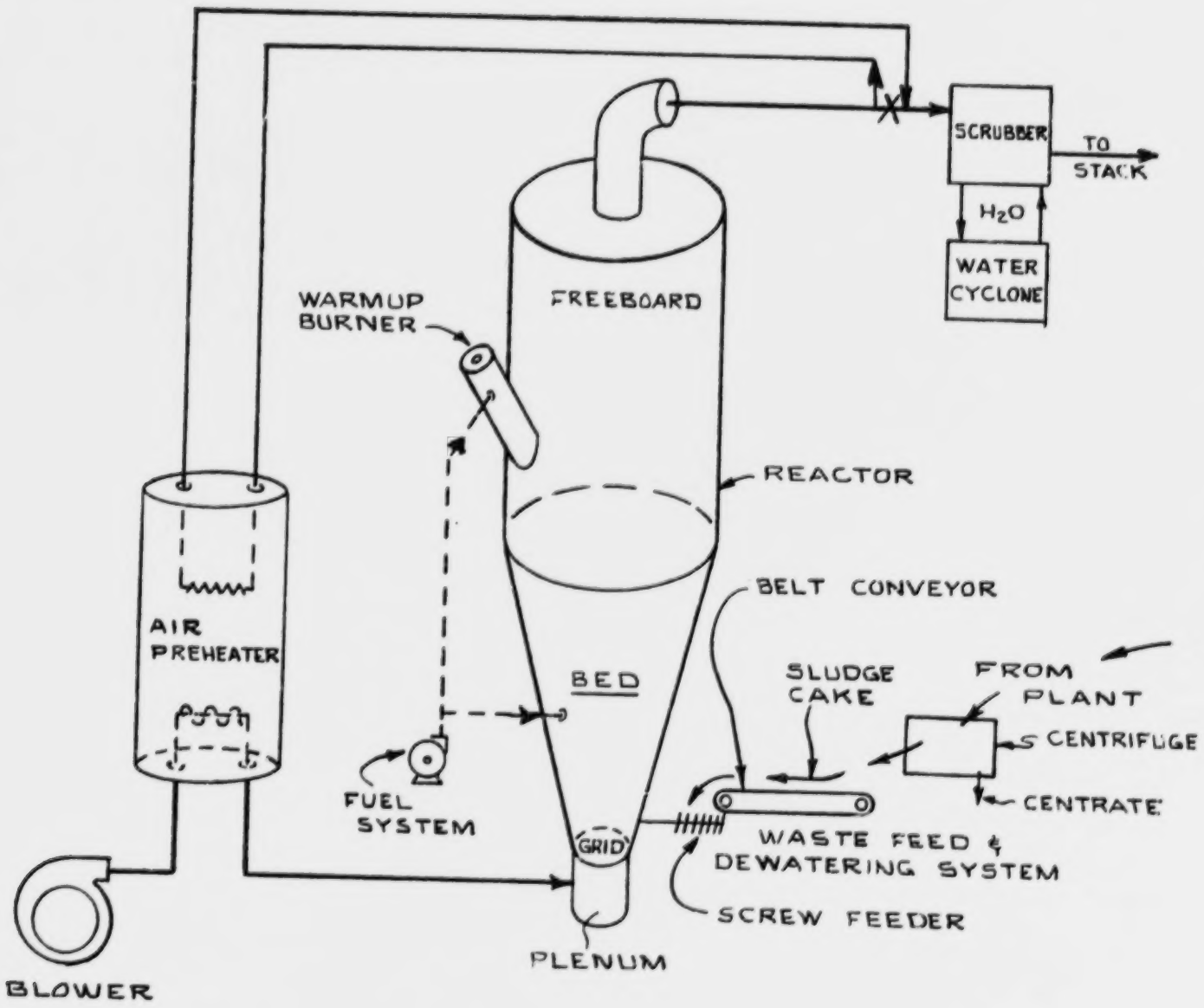


Figure 2

SYSTEM COMPONENTS INCLUDED IN STUDY

METHOD OF APPROACH

As the initial step in this program, it was necessary to secure complete representative data on the fluidized bed incinerator. The procedure used is described below.

Information and Data Gathering

Literature Survey

A review of the literature revealed that the first fluidized bed incinerator in the U.S.A. was installed in 1962 in Lynwood, Washington. Information was also available on one or two other installations; however, it soon became apparent that there was insufficient information available in the literature to generate a model. However, since about 30 new installations were either recently placed on stream or were in the design stage, a survey of equipment manufacturers was initiated.

Manufacturers Survey

A letter of inquiry together with an information sheet was directed to manufacturers advising that we were engaged in an FWPCA program and requesting cooperation in securing the necessary information. Very little data were obtained from manufacturers.

Field Survey

At this point, it became apparent that the necessary information could only be obtained from field installations. Since a number of installations had been financed under the construction grants program of FWPCA, visits were made to selected FWPCA regional offices to secure design and cost data from plans submitted for a construction grant. Visits were made to regional offices in Chicago, Kansas City, Boston, San Francisco, and Edison, N. J.

Subsequently, visits were made to treatment plants selected on the basis of capacity, location and period of operation: Sheboygan, Wisconsin; Kansas City, Kansas; Barstow, California; Port Heuneme, California; East Cliff, Sanitary District, Santa Cruz, California; Foster City, California; Fairfield Suisan City, California; Liberty, New York; Hazelton, Pa.; and Pleasantville, N. J.

RESULTS

Data Collected

A summary of the data collected during the field survey is presented in Tables I and II.

The equipment sizing and cost data are very reliable since they were obtained from visual inspection or files. However, the data for operating costs (fuel consumption, power consumption, operator costs, etc.) were not readily available, since accurate operating records were not generally maintained at the plants.

Since the plants surveyed were purchased at different times, a standard cost reference date of February, 1968 was chosen for this program. All unit prices were corrected to February, 1968 prices, using the Department of the Interior cost index for sewage treatment plant costs as presented in the Engineering News-Record Magazine.

Equations Developed

Equations were developed from this data and an FWPCA report (Reference 1). The data were plotted using various correlations; least square curves were plotted using least squares fit equations generated by computer.

Obviously, not all of the correlations attempted were successful. Many were discarded and equations were developed for only the best correlations found relating the variables of interest.

Theoretical vs. Pilot Plant Data

The fuel needed to raise sludge combustion products to a selected temperature can be determined from either theoretical calculations or pilot plant data. Note that in the discussion below, # indicates pounds and refers to the weight of solids plus water in the sludge cake (dry solids are referred to as PDS).

The variables needed for fuel rate determinations are:

1) BAF = combustion air required @ 4% excess ϕ_2, # air/# sludge

2) QF = required heat from fuel, Btu/# sludge

3) QLE = heat loss from pilot equipment which fuel must supply (zero for theoretical calculations), Btu/# sludge

4) QPE = heat supply to the combustion air by air preheater in pilot plant tests (zero for theoretical calculations), Btu/# sludge.

TABLE I FIELD

	LOCATION	STARTUP DATE / YEAR PURCHASED	LBS..DRY SOLIDS PER HOUR	PERCENT H_2O	PERCENT VOLATILE SOLIDS	Btu Per Lb. VOLATILE SOLIDS	INSIDE FREEBOARD DIAMETER, Ft.	OUTSIDE FREEBOARD DIAMETER, Ft.	FREEBOARD INSIDE CROSS-SECTIONAL AREA, $Ft.^2$	REACTOR OVERALL HEIGHT, Ft.	PLENUM HEIGHT, Ft.	STATIC BED DEPTH, Ft.	STATIC DEPTH PEA GRAVEL IN BED, Ft.	STATIC BED FREEBOARD, Ft.	AIR PREHEATER (Btu/min., °F)
1	Barstow, Calif.	8-68 / 1967	Design 500 Normal - Actual -	68	75	10,000	5.66	9.0	25.2	22	3.25	5	None	13.75	No
2	East Cliff Santa Cruz, Calif.	4-64 / 1963	Design 550 Normal 250 Actual -	65	75	8,000	4.63	7.63	16.8	25.5	2.5	5	None	18	No
3	Round Hill, Nev.	/ 1966	Design 470 Normal - Actual -	76	80	10,000	≈ 5.00	8.00	19.6	30	± 8	--	None	--	Yes 12,400 Btu/ min. Air @ 1000°F
4	Port Hueneme, Calif.	4-65 / 1964	Design 250 Normal 215	65-70	75	9,500	4.00	6.00	12.00	20	1.5	6	None	12.5	No
5	New Rochelle, N. Y. (Pilot Plant)	1961 / 1960	Normal 125	60	70-80	10-12,000	1.83	3.00	2.62	12	--	2	None	--	No
6	Lynwood, Wash.	1963 / 1962	Design 220 Normal 155-250	65-70	50-75	10,000	≈ 2.00	3.75	3.14	16	--	--	None	--	No
7	Foster City, Calif.	12-68 / 1968	Design 500	70	75	5,000	6.00	8.00	28.3	12	3	2' to bottom of feed pipe	None	--	No
8	Fairfield Suisan, Calif.	1-67 / 1965	Design 500	55-70	75	9,500	8.00	11.00	50.5	22.5	4	5	None	--	No
9	Jefferson, Mo.	1969 / 1968	Design 950	67	70	10,000	≈ 8.50	11.50	57.0	23	≈ 5	≈ 5	--	≈ 13	No
10	Kansas City, Mo.	6-63 / 1965	Design 4910 Actual 6800 (2 units)	32 to 68 max. Avg. 50	47-61	10,000	12.3 (14.0 if as Hazelton)	16.3	2 units 119 each	28.6	5	5 incl. 8" pea gravel	8"	18.6	No
11	Liberty, N. Y.	9-67 / 1966	Design 282	72	--	9,500	6.00	8.00	28.3	20	3	5	None	12.0	No
12	Pleasantville, N. J.	1966 / 1965	Design 490	75	65-75	9,500	6.25	9.25	30.7	24	6	4	None	14.0	Yes
13	West Haven, N. J.	1969 / 1967	Design 875	70	80	10,000	9.00	11.75	63.5	22.25	--	--	--	--	No
14	South Windsor, Conn.	1969 / 1967	Design 500	67-78 67 design	65-75	9,500 to 10,000 design	≈ 5.75	8.75	26.0	24	≈ 4	--	--	--	No
15	Sheybogan, Wis.	7-68 / 1967	Design 1000	75	62	7,072	10.00	13	78.5	24	7	3.5	Yes	11	Yes
16	Norwalk, Conn.	1969 / 1967	Design 1210	70	70	10,000	10.00	12.5	78.5	21.5	--	--	--	--	No
17	Hazelton, Pa.	8-69 / 1965	Design 1904	75	55-60	7500-8000 10,000 contract	14.00	16.25	155.0	29.1	5	5 incl. 2-1/2" pea gravel	Yes 2-1/2"	15	Yes
18	Natchitoches, La.	1967 / 1966	Design 450	75	75	9,500	≈ 7.50	9.00	38.4	25	5	≈ 4	--	≈ 16	Yes 13,400 Btu/ min. Air @1000 °F

I FIELD DATA

STATIC BED FREEBOARD, Ft.	AIR PREHEATER (Btu/min., °F)	NUMBER OF SLUDGE FEED POINTS	SLUDGE FEED POINT DISTANCE ABOVE GRID, Ft.	TYPE OF FEED DEVICE	TUYERES		TONS SAND IN BED	NUMBER OF CENTRIFUGES	NUMBER OF WARMUP BURNERS	WARMUP BURNER DISTANCES ABOVE GRID, Ft.	NUMBER OF BED BURNERS OR GUNS	BED BURNER LOCATION ABOVE GRID, Ft.	INSTALLATION FLOOR AREA	NUMBER WATER COOLING SPRAYS AND LOCATION	SCRUBBER SIZE
					NUMBER	SIZE & NO. HOLES									
13.75	No	1	1	Screw	--	--	3	1	1 1.5×10^6 Btu/Hr	--	Bloom Engr. Co. -- Installed	--	32' H x 15'W x 18' L + control room		2.5' dia 7' H 40 trays
18	No	1	2.5	Screw	--	--	4	1	33-36 gal/day 2 .58 gpm total	3.5	Not normally used .174 gpm Installed	2	30'H x 18'W x 32'L + control roo	1 @ scrubber inlet	Doyle 3' x 4.5' x 1.6'
--	Yes 12,400 Btu/ min. Air @ 1000°F	1	--	Screw or Moyno	--	--	--	2 @ 30 HP	--	--	0.5 gph normal installed	--	--	--	--
12.5	No	1	1	Screw	13- 1" pipe	1/8" dia 16 holes	2-1/2	1	Normal 1 @ 0.12 gpm	10.5	2 @ x gph ea.	3.5	Located Outside	1 in freeboard	L=46" W=18" H= -
--	No	1	--	(pneu-matic failed) Screw	--	--	--	--	--	--	--	--	--	--	--
--	No	1	--	Retract-able Screw	--	--	--	1 @ 20 HP	--	--	--	--	--	--	--
--	No	1	--	Screw	1-1/4" pipe on 6" cen-ters		--	1	1 1.5×10^6 Btu/Hr	4	2 @ .048 gpm total	1.5	25'L x 37'W x 16'H + control room	1	--
--	No	1	2	Screw	42'	--	5	1	1.5×10^6 Btu/Hr 1 Max. .02 gpm	--	3 @ 120° Not normally used	≈ 1' or less	30'L x 19'W x 18'H + control room	1 in free-board 1 @ scrubber inlet	--
13	No	--	--	Screw	--	--	--	2 @ 30 HP	4×10^5 Btu/Hr	--	several	--	--	--	--
18.6	No	2/unit @ 120°	1/unit	Screw	--	1/8" ≈10/ Tuyere	40 per unit	12	1/unit	7.3	6/unit	1.3	80'L x 80'W x 29'H + control room	4 @ roof freeboard 1 @ scrubber inlet	6' x 10' x 15'
12.0	No	1	1	Screw & Flexible Line	37- 1" pipe	1/8"	5	1	.85 gpm max.	Above Bed	2	1 @ 180°	30'L x 20'W x 25'H + control room	1 before scrubber	Std. Doyle 850°F inlet 195°F outlet
14.0	Yes	1	1	Screw & Flexible Line	--	--	2-1/2	1	1 1.7×10^6 Btu/Hr	Windbox	≈ 200 gal 3 weeks 2 installed ≈ 5 gph	In bed	22'L x 18'W x 35'H	1 in free-board 1 in plenum	3' dia 8' high
--	No	1	--	Screw	--	--	--	Not in Contract	1 2.5×10^6 Btu/Hr	--	2	--	63'L x 20'W x 35'H + control room	--	--
--	No	1	--	Screw	--	--	--	1	1 1.5×10^6 Btu/Hr	--	Installed	--	24'L x 1[illegible]'W x 35'H incl. control room	--	--
11	Yes	1	1-2	Screw	--	--	--	Vacuum Filter None	1	Windbox	3	--	≈20'L x 30'W x 25'H + control room	1 @ heat exchanger inlet	5' dia 15' H
--	No	1	--	Screw or Moyno	--	--	--	Not in Contract	1 2.5×10^6 Btu/Hr	--	Installed	In bed	30'L x 30'W x 40'H	--	2010 scfm @ 400°F
15	Yes	4	1 @ 90°	Moyno & Flexible Lines	≈ 180	1/16" dia 12 per Tuyere	40	Vacuum Filter None	1.6 gpm 1 10×10^6 Btu/Hr	Windbox	.6 gpm ea. 4 Bloom Engr.	1 above grid @ 90°	60'L x 40'W x 30'H	6 scrubber	6' dia 31' 10'L
16	Yes 13,600 Btu/ min. Air @1000 °F	1	≈ 1	Moyno or Screw	--	--	--	1	1 2×10^6 Btu/Hr	Windbox	0.5 gph	≈ 1	82'L x 44'W x 35'H	--	3150 scfm @ 400°F

B

TABLE II FIELD

SCRUBBER GPM	FUEL TYPE	MAJOR PROBLEMS	TOTAL INSTALLED HP ON INCINERATOR LESS CENTRIFUGE & ASH SYSTEM	PREHEAT BLOWER RATING			FLUIDIZED BLOWER RATING			FLOCCULENT		PLENUM TEMP., °F	NORMAL BED TEMP., °F / NORMAL INCIPIENT FLU. TEMP., °F	PLENUM PRESS. in H2O
				HP (IF USED)	SCFM	INCHES H_2O	HP	SCFM	INCHES H_2O	TYPE	DOSE			
10-20	#2 Diesel oil	--	≈ 80 installed 50 operating	7.5	483	--	50	--	-	Rohm & Haas Primafloc C-7	--	--	1400+ / 1500	
2	#2 Diesel oil	None	40 installed 24.7 operating	None			0	640 run 1000 rated	50 110	None	--	160 to 180	1300 to 1400 / 1370 to 1510	
--	--	--	--	None			50	1500 rated 650 max.	110	--	--	--	-- / --	
10-25	550 gal per mo. $98/mo.	Placement of Instrumentation	≈ 20	2 HP	--	--	15	450 rated	116	Rohm & Haas C-7	--	150	1700 - 1800 / 1500 - 1640	
--	--	Change pneumatic feed to screw	--	None			--	92/159 run	27/42	--	--	170	1280/1550 / 1660	
40	Startup 45¢/Ton Ds operate $1.62/ton Ds #2 Fuel oil	--	24.5	2.0	--	--	45	840 run	--	--	--	--	1350 to 1400 / 1350 to 1500	
--	#2 Fuel oil	--	42	None			30 to 40	800 rated 775 600 600	110 110 129 146	None	--	--	-- / --	
--	#2 Fuel oil	Bed gun burned off	≈ 45	10	575	68	30	1000 rated 980 running	110	None	--	--	1440 Max. 1500 / 1400	
2800 cfm outlet gas	#2 Fuel oil	--	90 HP blowers	15	1150	56	75	2500	110	Conditioning system supplied	--	--	-- / --	
800 to 1280	Natural Gas	Silo to feed jams screw conveyors	190	2 @ 20	2480 ea	56	2 @ 125 HP	8630 total run - data available 2 blowers ea 4600	110	None	--	160	1520 1600 normal / 1600 normal	
--	#2 Fuel oil	Centrifuge noise in operating area	42	5	450	42	30	820 run 1000 rated	110	Rohm & Haas Primafloc	10#/80 gal H_2O	160	1600 / 1600	
--	#2 Fuel oil	Initial refractory sand leak to plenum jamming feed line	43	None			40	950 run 1150 rated	≈60 124	Rohm & Haas Primafloc C-7	12#/75 gal Feed 35 gpd	160 600 max.	1400 / --	
feed 9% ash 20	#2 Fuel oil	--	≈ 84	7.5	840	42	60	1900 rated	110	--	--	--	1400 / --	
--	#2 Fuel oil	--	45	3	450	42	30	1000	110	--	--	--	1400 / --	
--	oil	Normal initial adj. at mo. startup	100 HP blower	None			100	2000	84	--	--	1500	1500 / 1550	≈40
--	#2 Fuel oil	--	85	7.5	840	42	75	2500	110	--	--	--	1400+ / --	
150	#2 Fuel oil	Wet turnings run off & lime pptn. mar	200		--	--	150	Min. Fluidization 1000 4000 run 5000 rated	80	Low Cost, A-21	20#/80 gal 7#/75 gal Feed 20 gal/hr feed	1200 to 1300	1250 / 1460 Air Heater Inlet 1500	65
Feed 9%	oil	--	--	None			40	1200	110	--	--	--	1400 / --	--

A

LE II FIELD DATA

NORMAL BED EMP., °F / NORMAL EXHAUST GAS EMP., °F	PLENUM PRESSURE, Inches H_2O	ΔP PLATE ΔP, Inches H_2O	WET PRESSURE, Inches H_2O	FREEBOARD PRESSURE, Inches H_2O	TORQUED FLAT PRESSURE, Inches H_2O	TARE LOAD RATE, Lbs/Hr.	PERCENT O_2 IN EXHAUST	CYCLE WET WARM-UP TIME, Hrs	BED COOLING RATE, °F/Hr	ORGANICS IN ASH	ASH DISPOSAL METHOD	TOTAL SYSTEM COST/DATE	Location
1400+ / 2500	[illegible]	--	--	--	--	--	--	--	--	--	Pond on Site	--	1
[illegible] 400 / [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	--	[illegible] plant oper. [illegible] cut	--	[illegible] days 100°F/hr	110°F in [illegible] hrs	--	Dump on Property	$141,500	2
-- / --	--	--	--	--	--	--	--	--	--	--	--	--	3
[illegible] / 1500 - 1540	[illegible]	--	[illegible]	[illegible]	--	--	--	[illegible] days	--	No	Dump on Site	$107,000 [illegible]	4
[illegible] / 1600	[illegible]	--	[illegible]	[illegible]	--	--	--	--	--	--	--	--	5
[illegible] / [illegible]	--	--	--	--	--	--	[illegible] Excess Air	--	--	--	--	--	6
-- / --	--	--	--	--	--	--	--	--	--	--	Trucked & Buried	$205,000	7
1440 Max. / [illegible]	[illegible]	[illegible]	--	[illegible]	--	[illegible]	[illegible]	--	--	None No bacteria	Pumped to field	--	8
-- / --	--	--	--	--	--	--	--	--	15°F/hr @ 1500°F	--	--	--	9
1520 1600 normal / 1400 normal	[illegible]	--	[illegible]	--	[illegible]	[illegible] lbs/sq. 100#/day for [illegible] units	[illegible]	48 hrs 1/2 hr on normal	40°F/ 16 hrs	None No bacteria @ 1600°F	Dump on Site	$675,000	10
[illegible] / 1500	[illegible]	[illegible]	[illegible]	15	--	Add 400#/ no. - sand fall thru .008"/sec.	[illegible]	long	400°F/ 24 hrs	--	Dump on Property	$191,000 Incl. $22,500 bldg.	11
[illegible] / --	[illegible]	[illegible]	55	8	--	[illegible]#/no.	[illegible]	24 hrs	40°F/hr max. @ 1500°F	--	Dump on Property	$13,000 Air [illegible] Water $[illegible],000 Total	12
1500 / --	--	--	--	--	--	--	--	--	15°F/hr @ 1500°F	--	--	$[illegible],000	13
[illegible] / --	--	--	--	--	--	--	6	--	15°F/hr @ 1500°F	--	--	$209,554	14
1540 / 1450	[illegible] to 7%	--	45	13	11	100	4	--	10-20°F/hr @ 1500	--	Trucked to Dump	$320,400	15
1400+ / --	--	--	--	--	--	--	--	--	15°/hr @ 1500	--	--	$222,100	16
[illegible] / 1440 Air Heater Inlet 400	[illegible]	15	40	15	--	[illegible] lbs.	[illegible]	75-100°F/hr to 1000°F	25°F/hr @ 1500°F	--	Trucked to Dump	$[illegible],000 Incls. all Over Equip.	17
[illegible] / --	--	--	--	--	--	--	[illegible]	--	--	--	--	--	18

1

B

Pilot plant data are more accurate than theoretical data for the above variables for reasons explained in the next section.

The procedure for calculating BAF and QF follows. Given the elemental composition of the sludge volatile solids the complete combustion equation for stoichiometric conditions is:(Note:(C) represents elemental carbon whereas C represents the moles of $\emptyset_2$ required for stoichiometric combustion of the sludge volatile solids)

sludge volatile solids

$$A_1(C) + B_1(H_2) + C(\emptyset_2) + D(N_2) +$$

Fuel

$$FM\ [A_2(C) + B_2(H_2)] +$$

Sludge Air Fuel Air

$$X(\emptyset_2) + 3.76X\ (N_2) + F(\emptyset_2) + 3.76F\ (N_2)$$

Combustion Products

$$A_3\ (C\emptyset_2) + B_3\ (H_2\emptyset) + [\,D + 3.76\,(X + F)\,]\ (N_2) \qquad (1)$$

where (X + F) = XF by the terminology chosen. In this discussion X is the moles of $\emptyset_2$ required for stoichiometric combustion of the sludge and F is the moles of $\emptyset_2$ required for stoichiometric combustion of the fuel. Note that the sulphur content of the sludge has been neglected since its heat of combustion is usually negligible.

From equation (1) the moles of $C\emptyset_2$ in the exhaust is given as

$$A_3 = A_1 + FM\,(A_2) \qquad (2)$$

and the moles of water in the exhaust due to the combustion of the H_2 in the volatile solids and fuel is

$$B_3 = B^1 + FM\,(B_2) \qquad (3)$$

The value of X + F now redefined as XF is determined from equation (1) as

$$XF = A_3 + B_3/2.0 - C \qquad (4)$$

The pounds of volatile solids under consideration above is given by

$$PØVS = 12.0(A_1) + 2.0(B_1) + 32.0(C) + 28.0(D) \quad (5)$$

and the volatile solids plus the inert solids gives the pounds of dry solids under consideration as

$$PDSC = PØVS/(PVS/100.0) \quad (6)$$

Therefore the pounds of sludge (dry solids plus water) under consideration is

$$PS = 100.0\ (PDSC/(100.0 - PH2Ø)\ ) \quad (7)$$

and the pounds of water under consideration is

$$PPH2Ø = PS - PDSC \quad (8)$$

If the combustion products given by equation (1) are added to the water content of the sludge given by equation (8) the total moles of the combustion products for the stoichiometric mixture for the volatile solids under consideration is

$$PVT = A_3 + B_3 + D + 3.76(XF) + PPH2Ø/18.0 \quad (9)$$

where PPH2Ø/18.0 is the moles of water in the sludge. Note equation (9) neglects the inert solids which remain in solid form and contribute little to the total exhaust volume.

The operation of a fluidized bed incinerator is adjusted so that about 4% excess oxygen exists in the flue gas. To accomplish this concentration of oxygen, the moles of excess oxygen (Y) which must be added to the supply air is derived as follows. Four percent excess oxygen is defined as

$$0.04 = Y/(PVT + 4.76(Y))$$

where 4.76(Y) is the total moles of air for Y moles of oxygen. Solving this equation for Y yields

$$Y = 0.04\ (PVT)/.8096 \quad (10)$$

Then the total moles of the exhaust products at 4 percent excess oxygen is

$$PV4T = PVT + 4.76(Y) \quad (11)$$

The heat transported into the incinerator by the sludge is in two forms: the heat contained in the mixture (using 0°F enthalpy base) and the higher heat of combustion. The heat contained in the sludge entering the incinerator is

$$SCP = PS\ (1.0\ Btu/\#\ °F)\ (60°F) \quad (12)$$

assuming the sludge specific heat as 1.0 and an inlet temperature of 60°F the higher heating value of the sludge (QS) is given in Btu/# volatile solids. Therefore the higher heating value of the sludge Btu/# sludge containing a given percent of volatile solids (PVS) is

$$PSL = QS\ (P\emptyset VS)/PS \tag{13}$$

The heat content of the air entering the incinerator is

$$AIRCP = 4.76\ (XF + Y)\ (\overline{M})\ (C_p)\ (T)$$

where $\overline{M}$ = molecular weight of air (28.9)

C_p = specific heat of air (0.24 Btu/#°F)

T = temperature of air assumed as 60°F.

Substituting the indicated values yields

$$AIRCP = 1980.0\ (XF + Y) \tag{14}$$

Therefore the total heat supplied to the incinerator per pound of sludge is given by

$$THCPT = QSL + QFU\ (FM)\ (12.0\ A_2 + 2.0\ B_2) + AIRCP + SCP/PS \tag{15}$$

Next the total heat content needed to raise the exhaust products to 1400°F will be derived. The temperature of 1400°F was selected because the minimum operating temperature for fluidized bed incinerators is around 1300°F and a slight safety factor is desirable to assure sufficient odor and bacteria control. The heat content of the $C\emptyset_2$, $H_2\emptyset$, N_2, $\emptyset_2$ and inerts in the 1400°F exhaust products from the volatile solids considered in equation (1) and resultant sludge are respectively listed below in the general form.

$$CPC2\emptyset = (\text{moles})(\text{molecular weight})(\text{specific heat at } 1400°F)(1400°F)$$

$$CPC2\emptyset = A_3\ (44.0)(0.295)(1400.0) \tag{16}$$

$$CPH2\emptyset = (B_3 + PPH2\emptyset/18.0)(18.0)(0.555)(1400.0) \tag{17}$$

$$CP2N = (3.76(XF + Y))(28.0)(0.279)(1400.0) \tag{18}$$

$$CP2\emptyset = Y\ (32.0)(0.263)(1400.0) \tag{19}$$

$$CPIN = (PDSC - POVS)(0.24)(1400.0) \tag{20}^{a.}$$

If the sum of equations 16, 17, 18, 19 and 20 (SUMQ) is divided by PS, the heat content of the exhaust products per pound of sludge (THCPT) is determined.

$$THCPT = SUMQ/PS \tag{21}$$

a. Specific heat is approximated by using data from Reference 46.

The fuel rate and thus heat input to the incinerator adjusted by means of the mole multiplier FM. When the thermal balance is reached between the heat input to the incinerator and the heat content of the exhaust products the variables BAF and QF can be evaluated from the equations developed above. Thus since

$$BAF = (\text{moles air required})(\text{air molecular weight})/PS$$

$$BAF = 4.76\ (XF + Y)(28.9)/PS \qquad (22)$$

and

$$QF = (\text{moles fuel})(\text{fuel molecular weight})(\text{fuel heating value})/PS$$

$$QF = FM\ [12.0\ A_2 + 2.0\ B_2]\ QFU/PS \qquad (23)$$

Limitations of the Theoretical Determination of BAF and QF

An elemental analysis of sewage sludge volatile solids does not identify the various compounds containing these elements. This analysis would be extremely difficult to obtain. Therefore, when complete combustion equations are applied to data derived from an elemental analysis only an approximation of the air required for combustion is attainable. This is because the carbon may exist as C, CO, CO_2, CO_X and the combustion equations for these compositions would each yield different air requirements. Thus it is anticipated that the theoretical analysis set-up to determine BAF will yield a slightly higher than actual value for most sludges.

In addition the heating value of a sludge could be calculated based on the elemental analysis. However, the result would be in error for the same reasons given above. Therefore, since an elemental analysis must be obtained in the laboratory it is a simple matter to also perform a bomb calorimeter test on the sludge to determine the actual higher heating value (QS). Because of the availability of the data no attempt was made to calculate QS in the computer program developed.

Air Preheater Sizing

The economics of operation will partially depend on the quantity of fuel required to incinerate the sludge. An air preheater can be used to reduce the quantity of fuel required. The equations developed below allow the sizing of the air preheater so that a heat balance exists between the exhaust products and incoming air. Three restrictions placed on design are that the exhaust product temperature is 1400°F entering the air preheater and no less than 400°F leaving the preheater, and the air temperature leaving the preheater is held to 1000°F or less. These restrictions are based on the field data obtained and presented in Table I and II. A fourth restriction is that the total heat transfered in the air preheater cannot exceed that required from fuel and/or preheat in the pilot test or calculated theoretical fuel.

The derivation proceeds as follows. An air flow rate of BAF entering the air preheater at 60°F has a heat content of

$$QAIR = BAF\ (0.24\ Btu/\#°F)(60°F) = 15.0\ BAF \tag{23-a}$$

At 1400°F the exhaust products have a heat content of

$$QE = QSL + QF + QPE + QAIR - QLE \tag{24}$$

based on the equations 1 through 23.

An air preheater can transfer a quantity of heat into the supply air as long as this heat input does not exceed that determined from pilot tests or calculations as

$$QFP = QF + QPE \tag{25}$$

For a unit with no air preheater the fuel cost is

$$CF = FC\ (QFP)\ (PCTY)\ (8750.0)\ (CAP)/10^6 \tag{26}$$

where 8750.0 is the number of hours in one year. If the exhaust products are cooled from 1400°F to 400°F in the preheater the heat transfered per pound of sludge is

$$PC_1 = QE\ (CAP)\ \left(\frac{1400.0 - 400.0}{1000.0}\right) \tag{27}$$

Thus PC_1 is seen to represent the allowable heat which can be removed from the flue gas without causing undue condensation of the water in the flue gas. Condensation prevention is assured by holding the flue gas temperature around 400°F. The heat removed from the flue gas (PC_1) is transfered to the incoming combustion air.

To heat the incoming air from 60°F to 1000°F the air preheater would have to transfer

$$PC_2 = BAF\ (0.24)\ (1000.0 - 60.0) \tag{28}$$

where 0.24 Btu/# °F is the specific heat of air assumed as constant over the temperature range. The allowable air preheater heat transfer per pound of sludge is the lower of PC_1, PC_2 and QFP thus

$$APHS = PC_1 \text{ or } PC_2 \text{ or } QFP \tag{29}$$

whichever value is lowest. Note that this is the maximum heat transfer rate (and thus fuel saving rate) possible for the particular system.

Sizing the Reactor

The total heat release rate in the reactor is given by

$$SUMQ = (QSL + QFP)\,CAP + QL \qquad (30)$$

where QL is the heat loss rate from the reactor which must be generated by the heat of combustion. Figure 3 shows the best correlation found relating the grid area to the total heat release in the reactor namely

$$AG = SUMQ/155{,}000.0 \qquad (31)$$

This starting point was chosen because the heat release in an incinerator is closely related to the volume of the combustion chamber.

This correlation was obtained by omitting ("discounting") the data for the early units. Note that location 10 is shown as quoted insulation and Hazelton insulation. The point labeled "quoted insulation" was based on the grid sizing obtained from the firebrick thicknesses stated by plant personnel. The point labeled "Hazelton Insulation" was based on the refractory thickness known to be installed at Hazelton, Pa. Since the Hazelton unit was roughly the same size as those at Kansas City it seems likely that the refractory thickness would be very close for each of the units.

If the bed is considered as isothermal with combustion occurring near the lower portion of the bed the ratio of AF/AG would be 1.0 as shown in Figure 4 (assuming zero percent water content in the sludge). As water content of the sludge increases the expansion ratio AF/AG must be increased if gas velocity is to be maintained within tolerable limits at the top of the bed. This is because the volume of combustion products per pound of sludge increases when vaporization of the water and subsequent increases in fuel and air requirements occur. For practical purposes the ratio AF/AG cannot be allowed to increase beyond reason because of construction costs. Therefore an upper limit of AF/AG = 3 was arbitrarily chosen for 100% water conditions.

The combustion chamber for a fluidized bed is tapered so that the upper cross-sectional area at the freeboard is larger than the cross-sectional area at the grid. Such a taper prevents acceleration of combustion gases and thus limits sand loss and over-fluidization at the top of the sand bed. This taper was also found to be related to the water content of the sludge as shown in Figure 4.(3) Therefore the volume of the expanded bed (combustion chamber) is related to the grid area, sludge water content and sand bed depth. If the grid area is fixed then the sand bed depth is fixed for a given sludge.

Thus for design purposes either the grid area or bed volume could be selected first. The end result would be the same regardless of which parameter was selected.

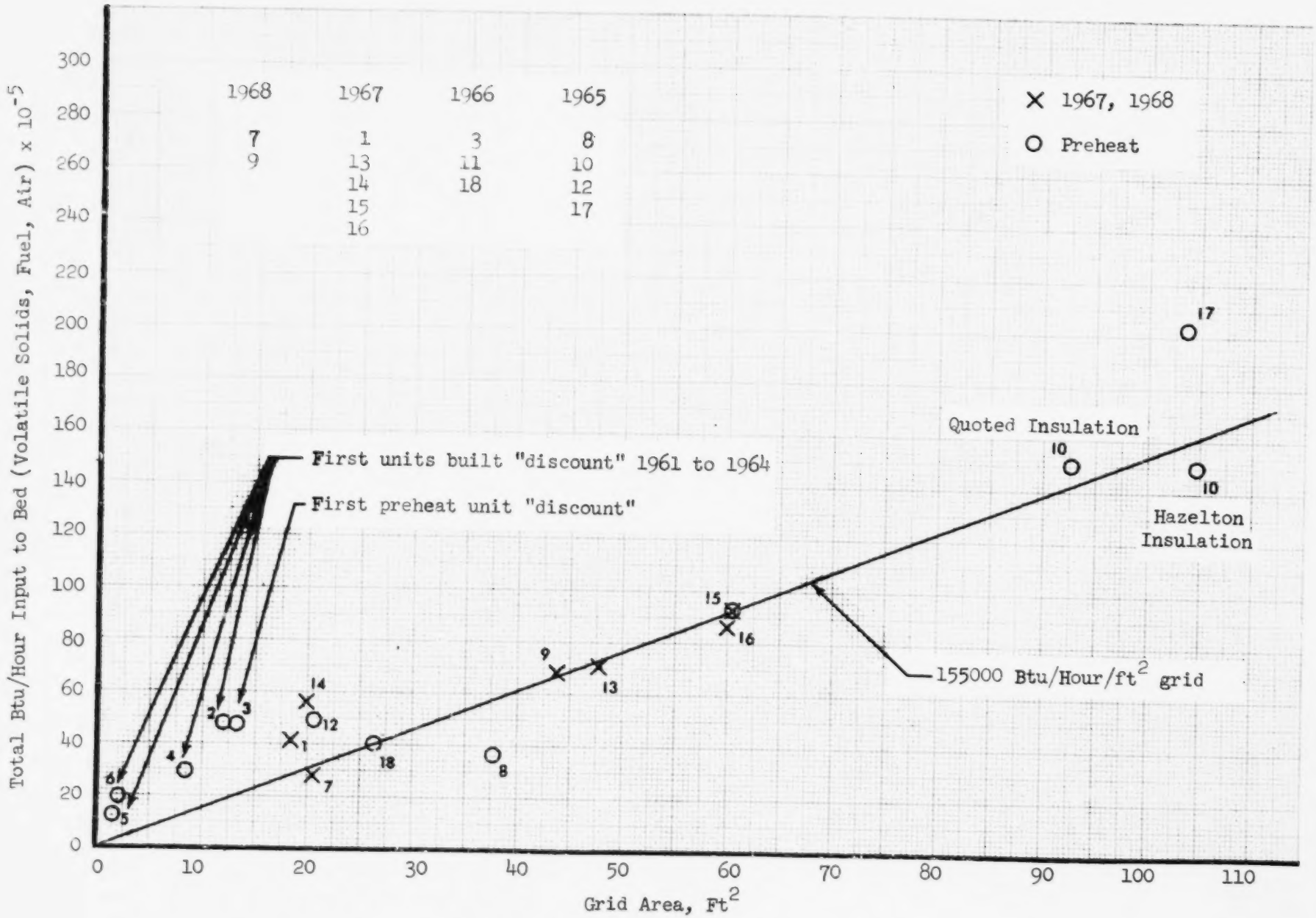


Figure 3 GRID SIZING

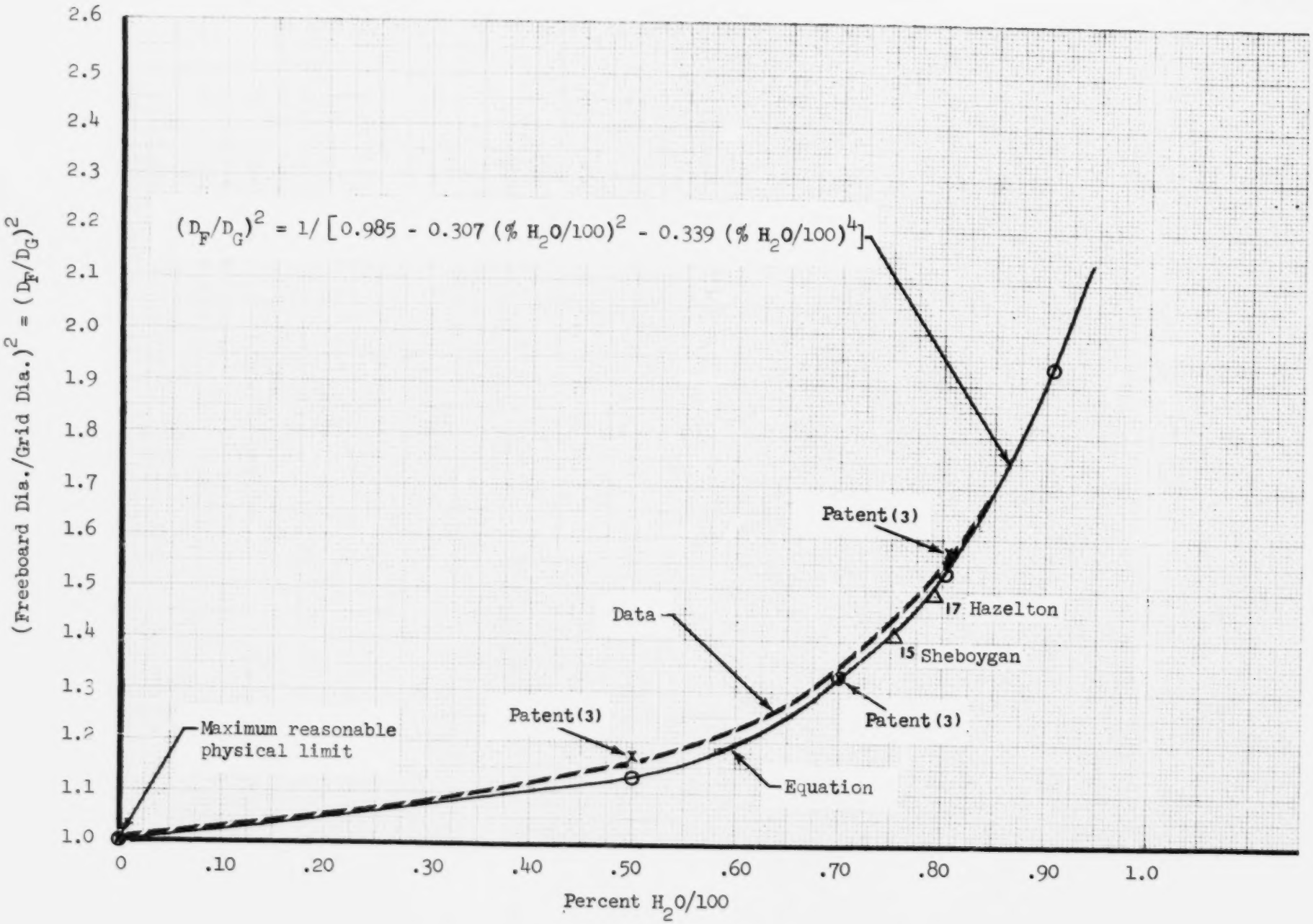


Figure 4 RELATION OF FREEBOARD DIAMETER TO GRID DIAMETER

From Figure 4 the freeboard area is found to be

$$AF = AG/\ 0.985 - 0.307\ ((PH2\emptyset/100.0)^2 - 0.339\ (PH2\emptyset/100.0)^4) \quad (32)$$

where $AF/AG = (DF/DG)^2$

Figure 5 shows the correlation developed for the expanded bed volume which yields

$$VE = SUMQ/18{,}000.0 \quad (33)$$

Since the bed volume is an inverted frustum of a cone having a volume VE the height of the frustum is given from geometry as

$$HE = VE/\ 1.047\ (AF/PI + (AF/PI)^{1/2}\ (AG/PI)^{1/2} + AG/PI) \quad (34)$$

The diameter of the grid (DG) and diameter of the freeboard (DF) are determined simply as

$$DG = (4\ (AG/PI))^{1/2} \quad (35)$$

$$DF = (4\ (AF/PI))^{1/2} \quad (36)$$

The standard practice appears to be to fluidize the sand bed until it reaches a volume of approximately 1.5 times the volume of the static bed. From this the static bed volume is determined as

$$VS = VE/1.5 \quad (37)$$

Figure 6 shows the correlation obtained for the height of the freeboard (HF)

$$HG = 1.6\ (HE) \quad (38)$$

Figure 7 is the best correlation found for determining the plenum volume. It seems reasonable since the combustion air requirements are somewhat related to the heat release in the reactor. The resultant equation relating the plenum volume to the total reactor heat input is

$$PV = SUMQ\ (2.5)/(10)^5 \quad (39)$$

Thus the plenum height (HP) is

$$HP = PV/AG \quad (40)$$

The overall reactor height is obtained by adding equations 34, 38, and 40 as

$$ORH = HE + HG + HP \quad (41)$$

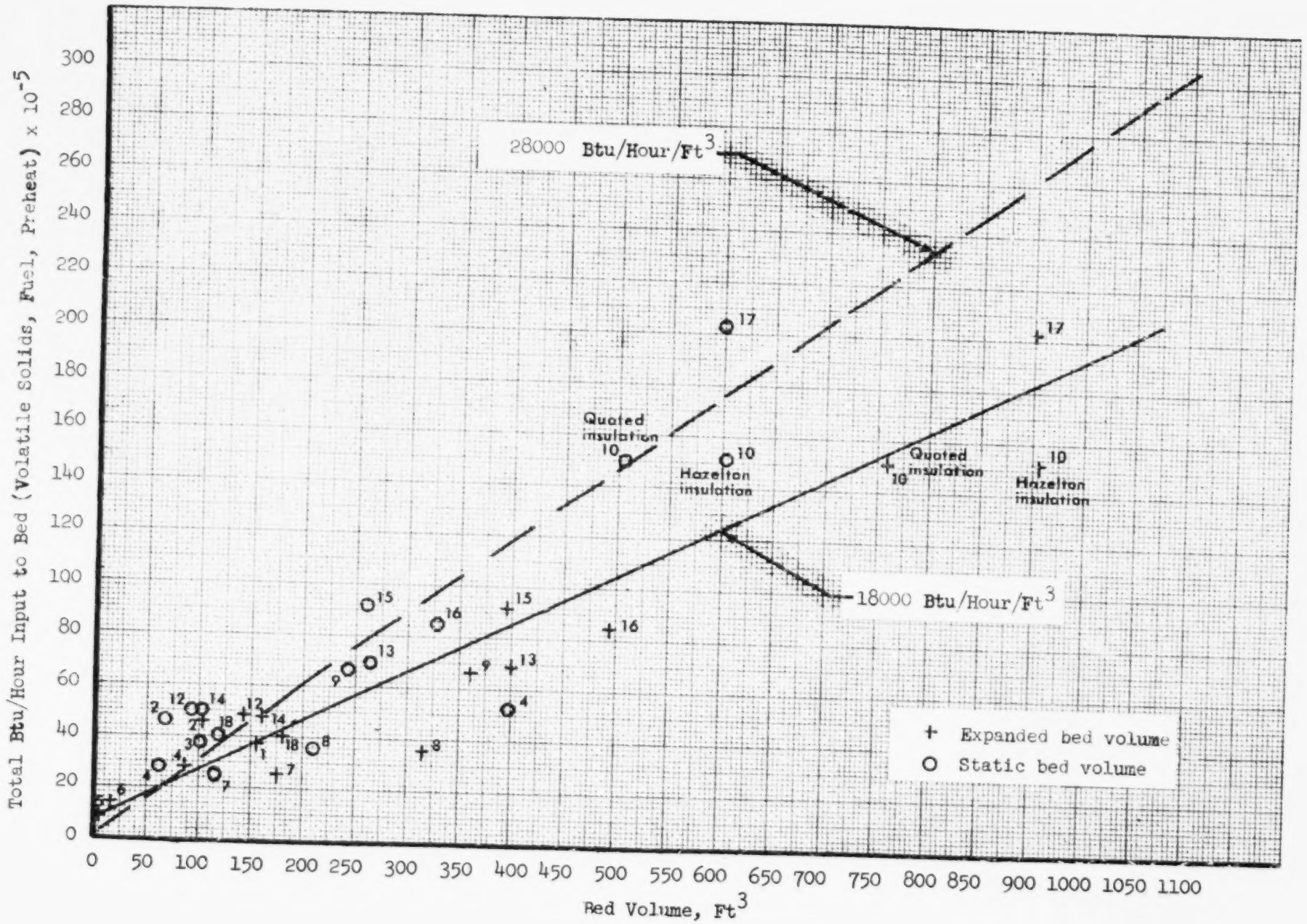

28000 Btu/Hour/Ft3
18000 Btu/Hour/Ft3
Quoted insulation
Hazelton insulation
Quoted insulation
Hazelton insulation
Expanded bed volume
Static bed volume
Total Btu/Hour Input to Bed (Volatile Solids, Fuel, Preheat) x 10-5
Bed Volume, Ft3
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750 800 850 900 1000 1050 1100

Figure 5 SAND BED SIZING

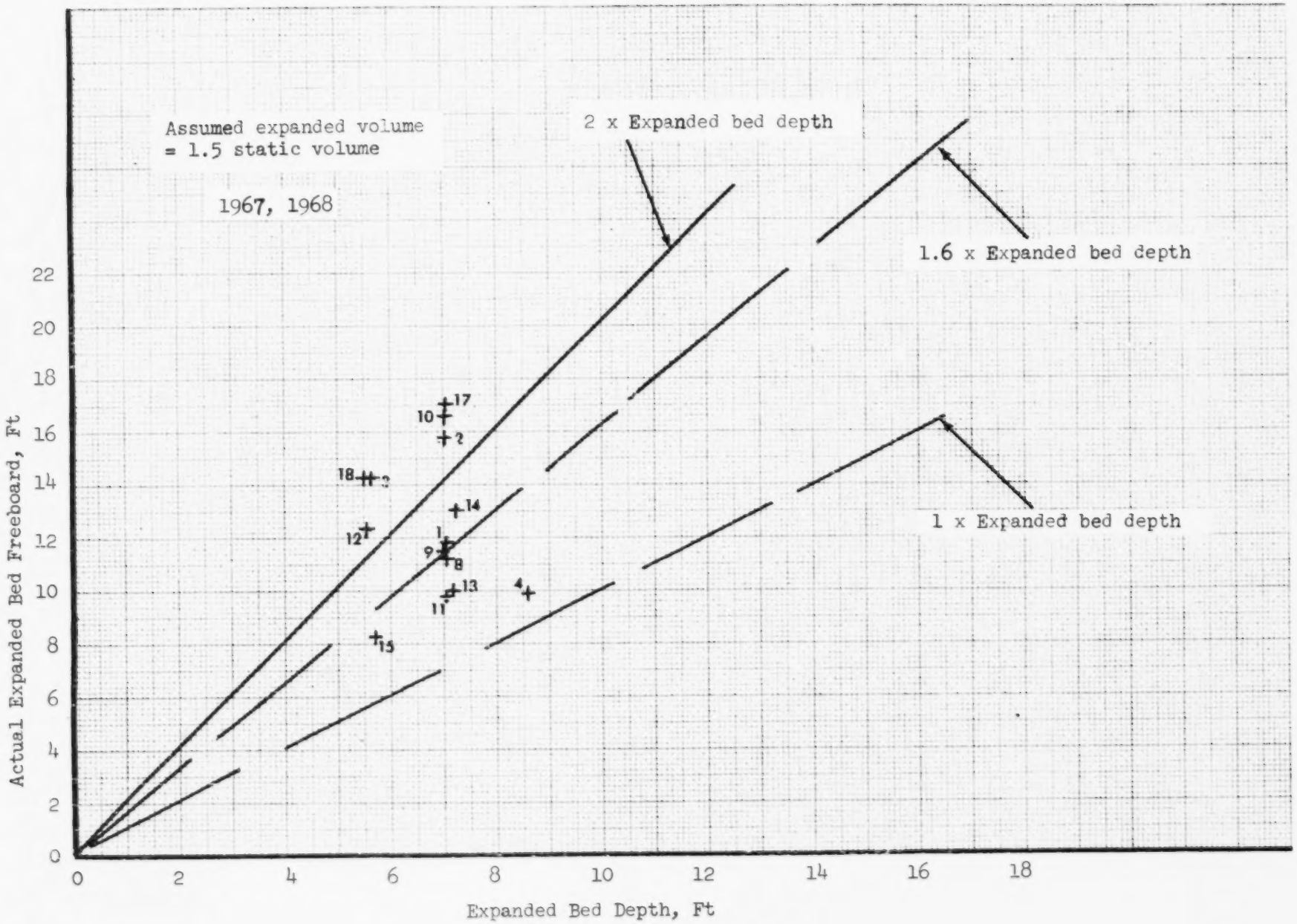


Figure 6 FREEBOARD SIZING

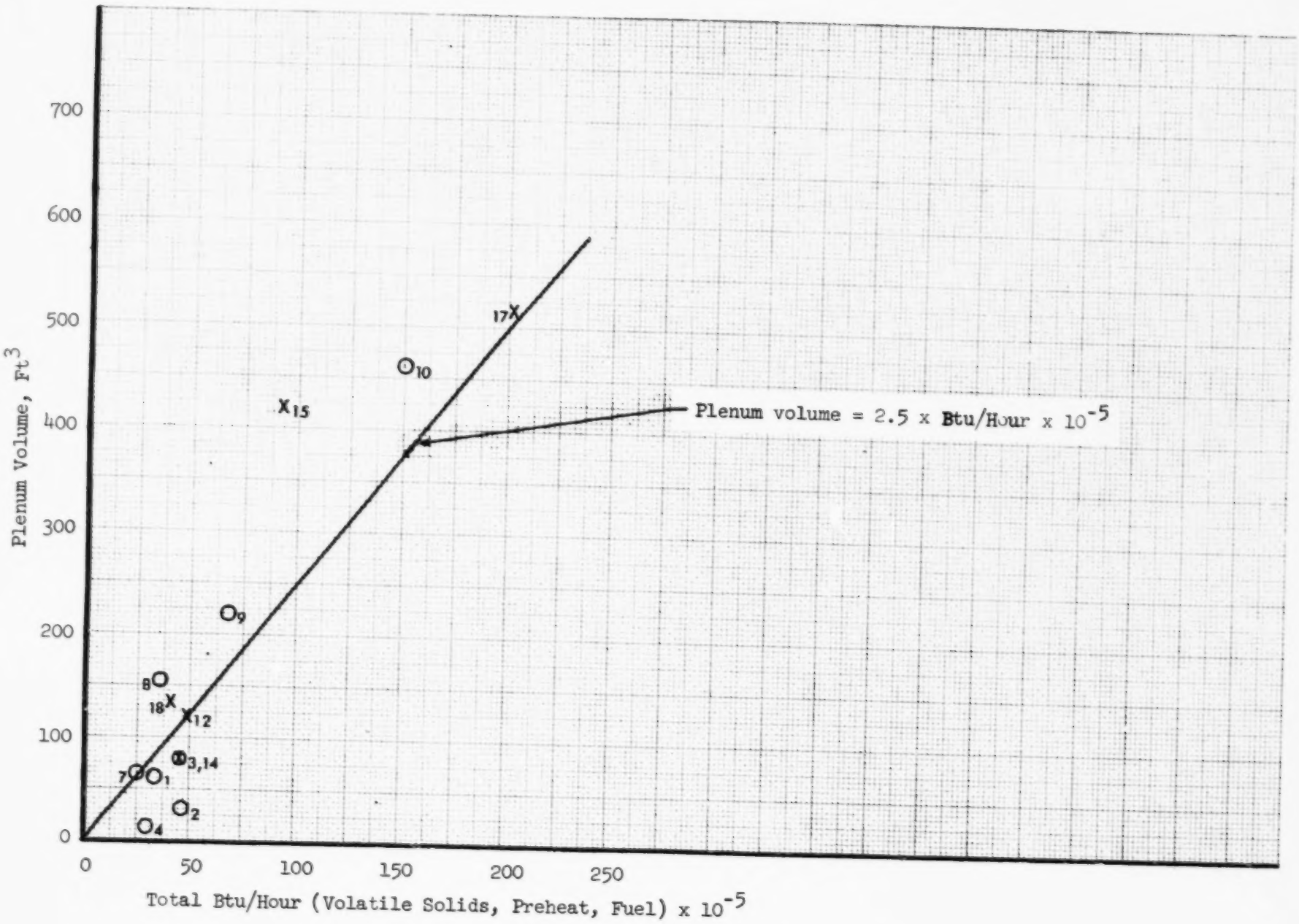


Figure 7 PLENUM SIZING

Neglecting the plenum the outside surface area of the reactor where heat is lost to the atmosphere is

$$A\emptyset = PI\,(HG(DF) + HE(DF + DG)/2.0) \tag{42}$$

Assuming a heat transfer convection coefficient of 4.0 Btu/hr-ft^2-°F, the convection heat loss from the outside surface of the reactor is

$$QLL = 4.0\,(A\emptyset)\,(TW - TA) \tag{43}$$

If the wall temperature (TW) and ambient air temperature surrounding the reactor (TA) are not given, values of

$$TW = 200.0°F$$

$$TA = 60.0°F$$

are adequate. Note that the radiation heat loss is negligible at wall temperatures in the range of 200°F. A well insulated reactor should not have wall temperatures in excess of 200°F because of the safety hazard of receiving burns.

Figure 8 shows the correlation developed for determining the number of sludge feed points installed in the bed section of the reactor. As the size of the incinerator is increased it becomes necessary to feed the sludge into the bed at several locations around the periphery of the bed to obtain full use of the fluidized bed incineration capacity. Thus the number of feed points required is given by

$$NFP = 100.0\,(PDS)/2000.0(PCDS) \tag{44}$$

where NFP is rounded off to the nearest integer.

System Power Requirements

The installed horsepower for the fluidized bed incinerator, based on field data is presented in Figure 9 as

$$HPI = 15.2 - 0.01024\,(PVSH) + 0.0001607\,(PVSH)^2 \tag{45}$$

This includes the power requirements for all components from the centrifuges through the ash system.

The fluidizing blower horsepower is included in the installed horsepower above. However, it may be of interest and it is plotted in Figure 10. The representative equation is

$$FBHP = -5.68 + 0.908\,HPI - 0.000565\,(HPI)^2 \tag{46}$$

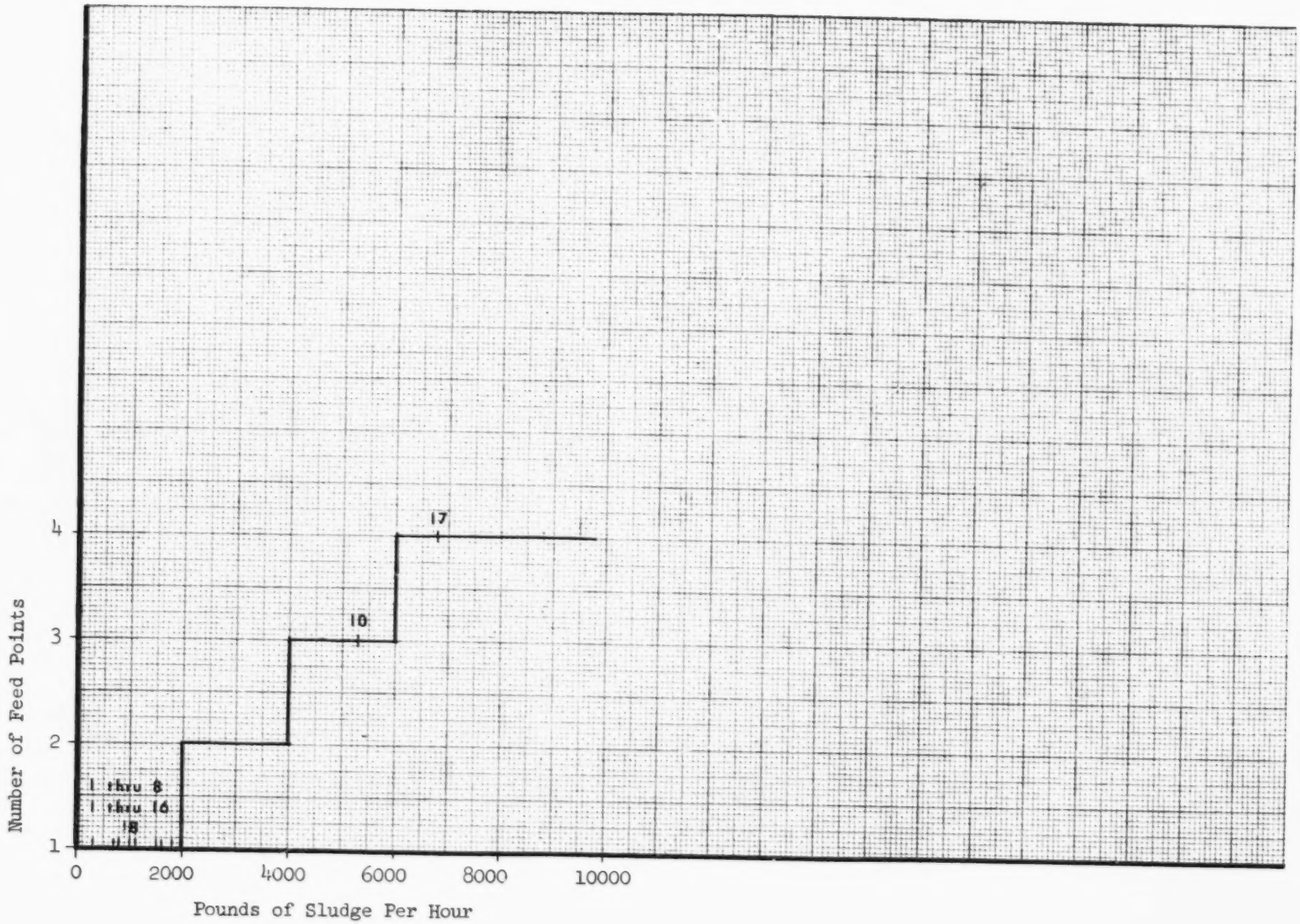


Figure 8 NUMBER OF REACTOR FEED POINTS

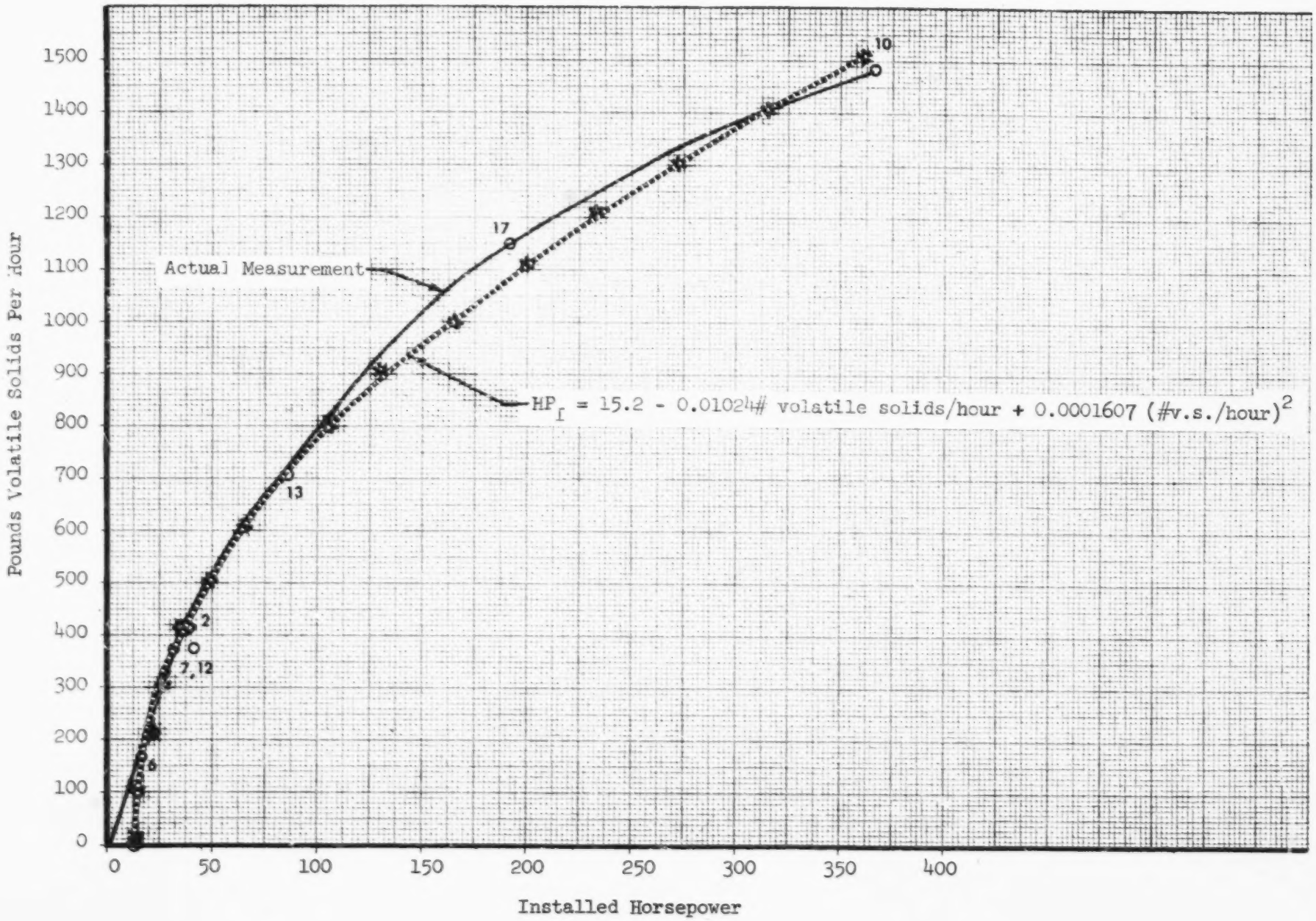


Figure 9 INSTALLED HORSEPOWER

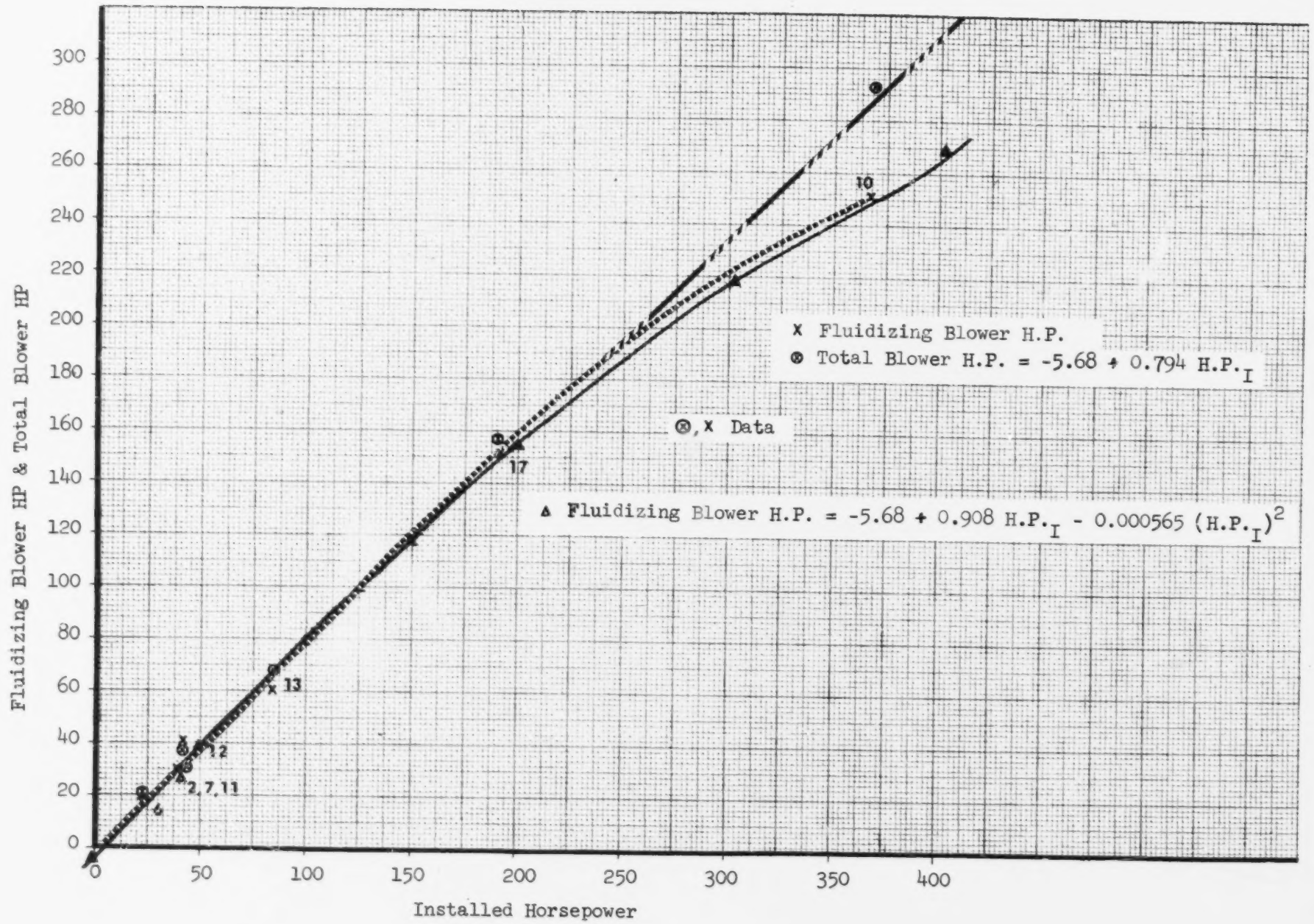


Figure 10 BLOWER HORSEPOWER

The operating horsepower for the system was found to be

$$OHP = 0.625\ (HPI) \tag{47}$$

based on the data obtained for locations 1 and 2 in Table, I, II.

Sand Loss Rate

Sand losses occur because of non-uniform particlesizes cause by sieving and attrition in the fluidized bed. The small particles are carried out more easily than the larger particles. To fully fluidize the bed a gas velocity is required which will fluidize the large particles. Since this is too high a velocity to allow retention of the smaller particles the small particles are gradually carried out the top of the bed. This sand loss rate can be reduced to reasonable levels by providing a sufficient freeboard height.

A plot of field data gathered on the sand loss rate from the bed caused by carryover in the exhaust gas is shown in Figure 11. The resultant equations are

$$SLR = (10350.0\ (DF/HF - 0.6)(PCTY)\ (8750.0)/30.0(8.0))\ (ZII) \tag{48}$$

for

$(DF/HF \geq 0.64)$ and

$$SLR = (632.0\ (DF)\ (PCTY)(8750.0)/30.0(8.0)(HF))\ (ZII) \tag{49}$$

for

$(DF/HF \leq 0.64)$.

In the above equations where 8750.0 is the total hours in one year, 30.0 is the average number of days per month and 8.0 is the number of hours per day the field units are operated.

Carbon and Hydrogen Content of Fuels

Based on data obtained from major oil companies (Mobil, American and Sinclair) the ratio of the moles of carbon to the moles of hydrogen in number two fuel oil ranges from 0.54 to 0.80. For the purpose of this program an average of the data collected (determined as 0.60) was used for the C/H ratio (i.e. 1.2 moles C for 1 mole H_2). For natural gas (CH_4) there is 1 mole of C for 2 moles of H_2.

System Costs

Cost Structure

The costs developed for this program include all components required

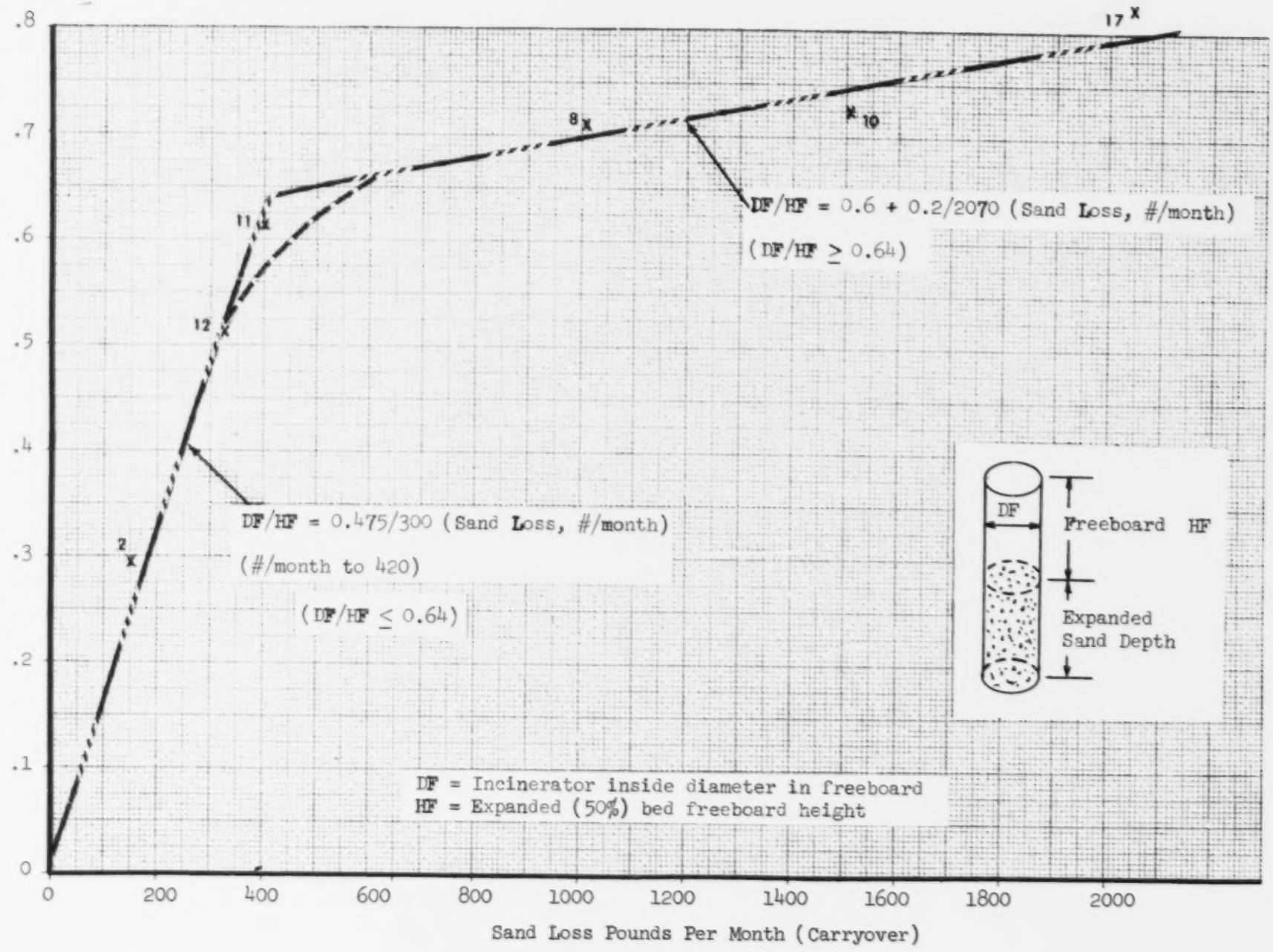


Figure 11 SAND LOSS RATE

for the fluidized bed incineration system less the building and land requirements. The components included in the cost data are:

1) Comminuter

2) Sludge Pump

3) Dewatering Devices (centrifuge)

4) Waste Feed System

5) Reactor

6) Scrubber

7) Ash-Water Separation System

8) Air Preheater

The centrifuge is the only dewatering device included in the cost analysis.

In addition to the basic system cost an installation fee of 10 percent must be added.[a] A Consulting Engineer's fee of 10 percent of the sum of the System Cost plus installation fee must also be added.[2]

System Cost Less Air Preheater

Figure 12 shows a plot of data presented in Reference 47. An overlay on this curve is shown representing the field data collected. There appears to be a significant discrepancy indicating that the manufacturers prices quoted in Figure 12 are higher than the actual selling prices for this equipment.

Table III shows the data from which the field data curve was plotted.

Since there was a significant difference in the cost data it was decided to use both the manufacturers quoted prices and the field data prices in the computer program for comparison purposes.

It was found that the field cost was correlated more closely by relating the cost to the capacity in pounds of volatile solids per hour. This plot is shown in Figure 13.

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a. Data from a conversation with Mr. Stewart Peterson, N.E. Region Program Director, F.W.P.C.A., Boston, Mass.

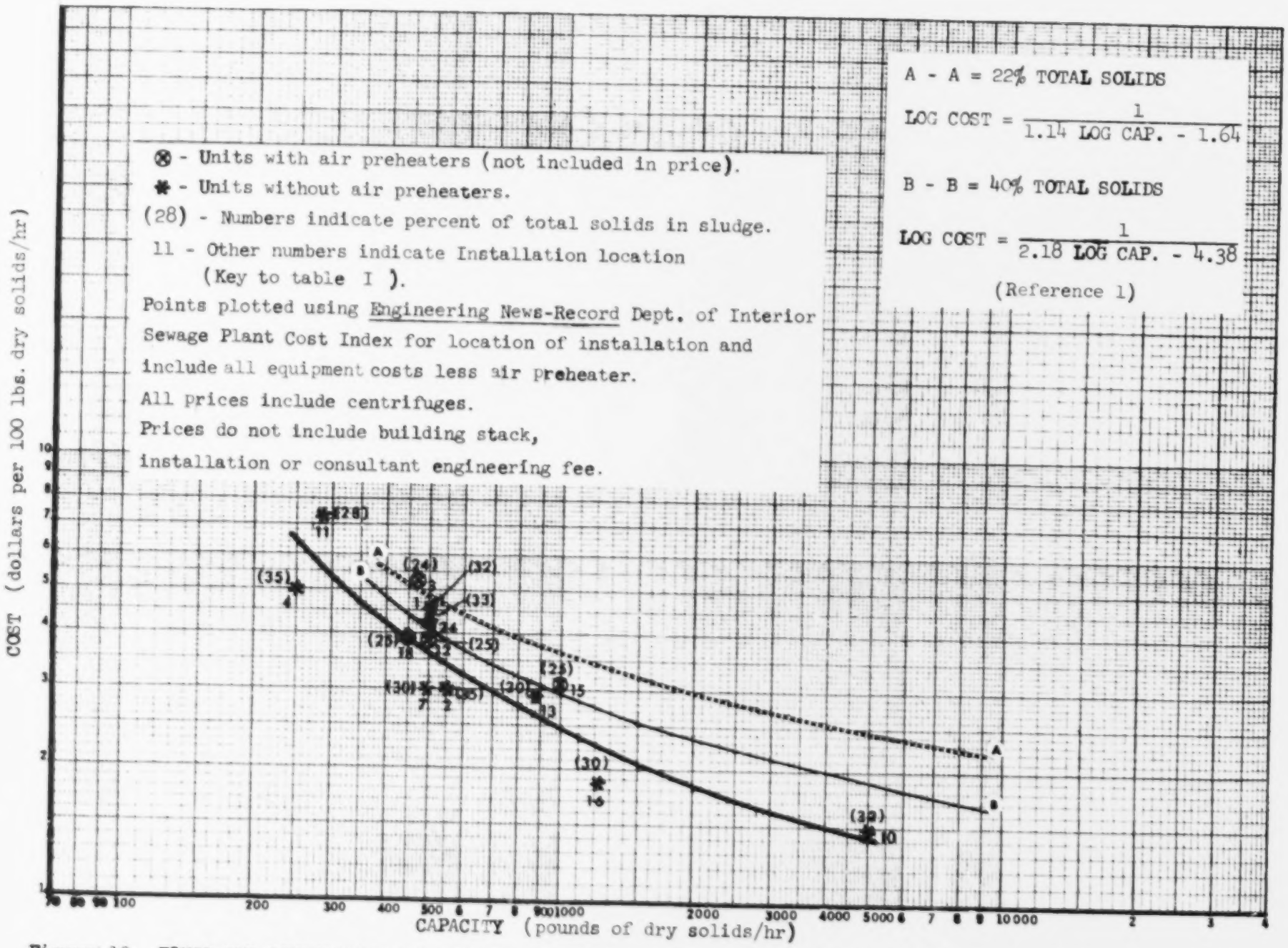
⊗ - Units with air preheaters (not included in price).
✱ - Units without air preheaters.
(28) - Numbers indicate percent of total solids in sludge.
11 - Other numbers indicate Installation location (Key to table I).
Points plotted using Engineering News-Record Dept. of Interior Sewage Plant Cost Index for location of installation and include all equipment costs less air preheater.
All prices include centrifuges.
Prices do not include building stack, installation or consultant engineering fee.
A - A = 22% TOTAL SOLIDS
LOG COST = 1 / 1.14 LOG CAP. - 1.64
B - B = 40% TOTAL SOLIDS
LOG COST = 1 / 2.18 LOG CAP. - 4.38
(Reference 1)
COST (dollars per 100 lbs. dry solids/hr)
CAPACITY (pounds of dry solids/hr)

Figure 12 FLUID BED COMBUSTION SYSTEM COSTS IN FEBRUARY 1968 DOLLARS - [dollars/(100 pounds of dry solids/hr)]

TABLE III

DATA USED TO DETERMINE SYSTEM COSTS

Location (Key to Table I & II)	System[a] Costs $	Cost[b] Multiplier	Design Capacity #DS/HR	$/100 #DS/HR
1	213,952	1.01	500	4.34
2	141,500	1.16	550	2.98
3	220,000	1.10	470	5.14
4	107,446	1.14	250	4.93
7	150,000	1.00	500	3.00
10	673,810	1.05	4910	1.44
11	191,000	1.05	282	7.14
12	174,880	1.08	490	3.87
13	254,030	1.01	875	2.94
14	205,554	1.01	500	4.15
15	308,600	1.01	1000	3.11
16	222,100	1.01	1210	1.85
18	172,600	1.04	450	3.98

a. Includes correction for air preheaters. Costs are for systems without air preheaters.

b. Based on Engineering News Record, Dept. of Interior Sewage Treatment Plant cost index from purchase date to February, 1968.

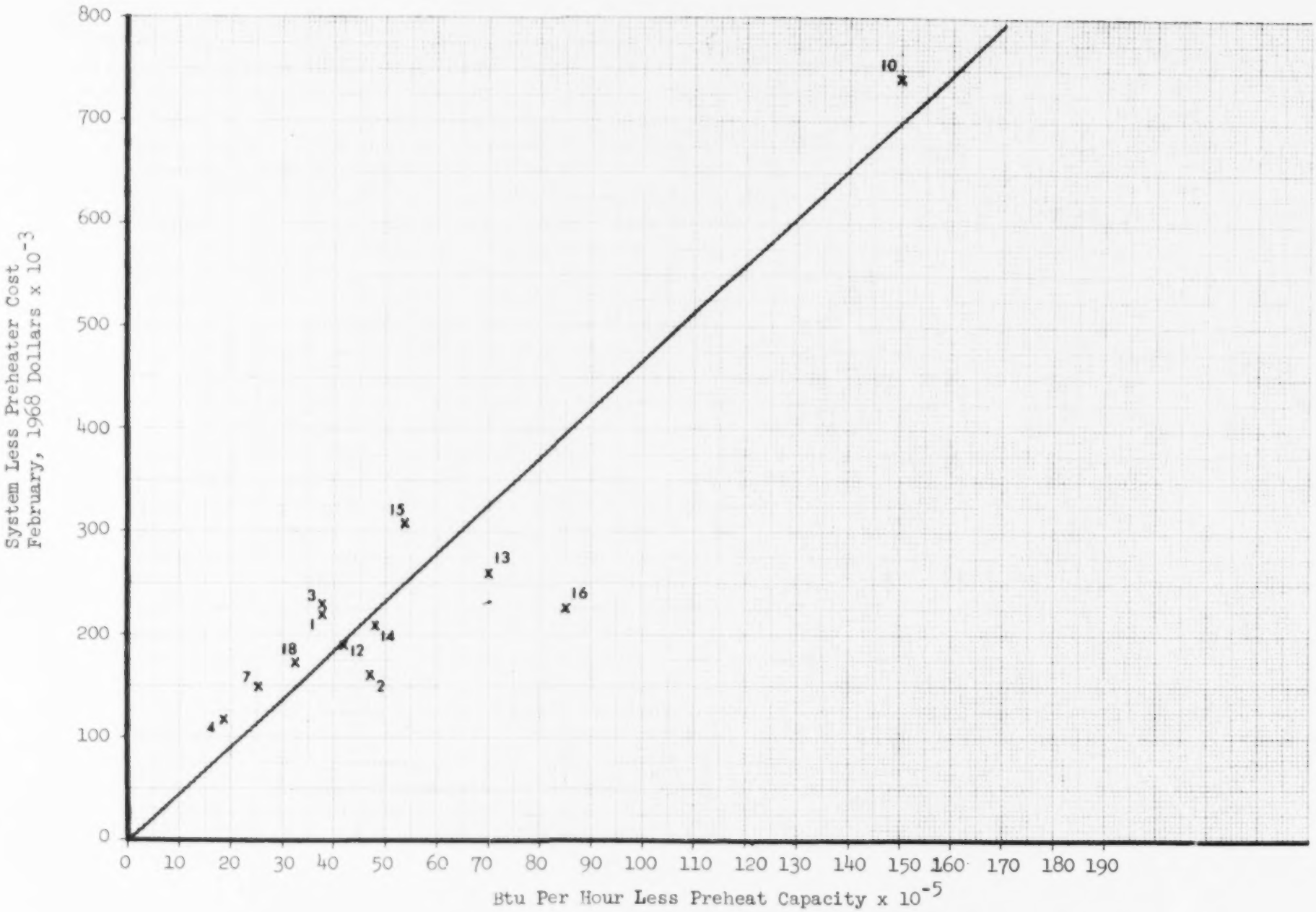

Figure 13 SYSTEM COST LESS AIR PREHEATER FEBRUARY 1968 DOLLARS

The equations resulting from Figure 12 for the manufacturers data are

$$C\emptyset RD = 1.0/(1.14(0.434294482)\ L\emptyset G_e\ (PDS) - 1.64)\ 100.0\ (PDS) \quad (50)$$

and

$$C\emptyset RD = 1.0/(2.18(0.434294482)\ L\emptyset G_e\ (PDS) - 4.38)\ 100.0\ (PDS) \quad (51)$$

for 22% and 40% respectively, total solids in the sludge.

The equation resulting from the field data plotted in Figure 13 is

$$C\emptyset R = 100{,}000.0 + 212.0\ (PVSH) \quad (52)$$

It is recommended that Equation 53 be used for costing the system less the Air Preheater cost.

Air Preheater Cost

From the sizing requirement defined on page 12, an air preheater can be costed using Figure 14. This figure shows a plot of air preheater cost versus size based on field data. From the data available the cost was found to be

$$APHC = 2.9\ (APHS)/60.0 \quad (53)$$

A linear relation was assumed because the heat transfer rate in an air preheater is directly proportional to the heat transfer surface area. This surface area is related to the amount of steel required to construct the preheater and thus to the cost. The configuration of the air preheater used in plants visited is shown in Figure 15. Alternate annular spaces carry hot exhaust gases and in the other annular spaces the air moves in counter-flow fashion.

Total Equipment Cost

The equipment cost is obtained by adding the reactor system costs (CØRD or CØR) to the air preheater cost (APHC)

$$ECD = C\emptyset RD + APHC \quad (54)$$

$$EC = C\emptyset R + APHC \quad (55)$$

Installation Fee

Based on the information described the installation fee is

$$CID = ECD/10.0 \quad (56)$$

$$CI = EC/10.0 \quad (57)$$

depending on the data used for costing.

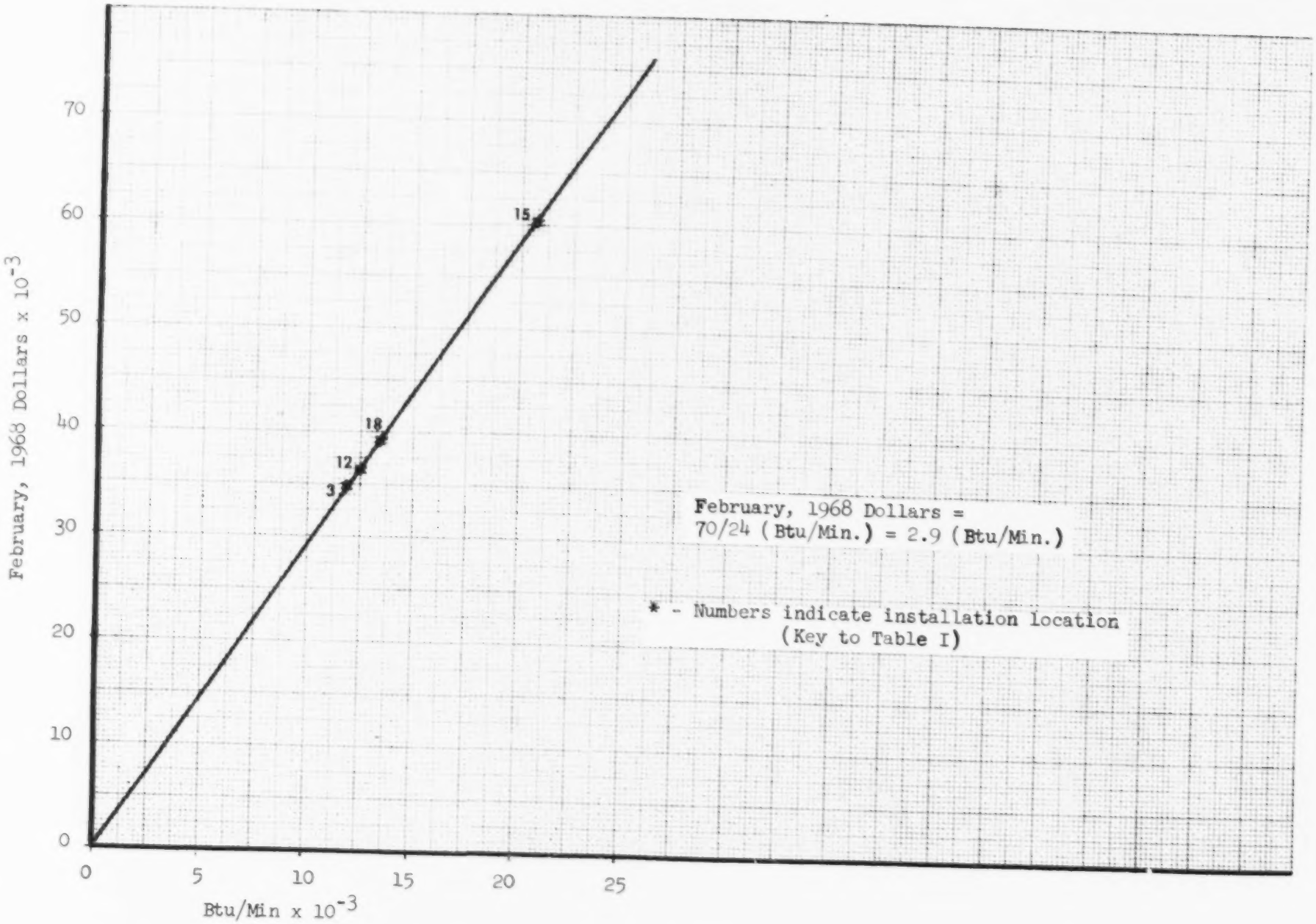

Figure 14 AIR PREHEATER COST VS CAPACITY FEBRUARY 1968 DOLLARS

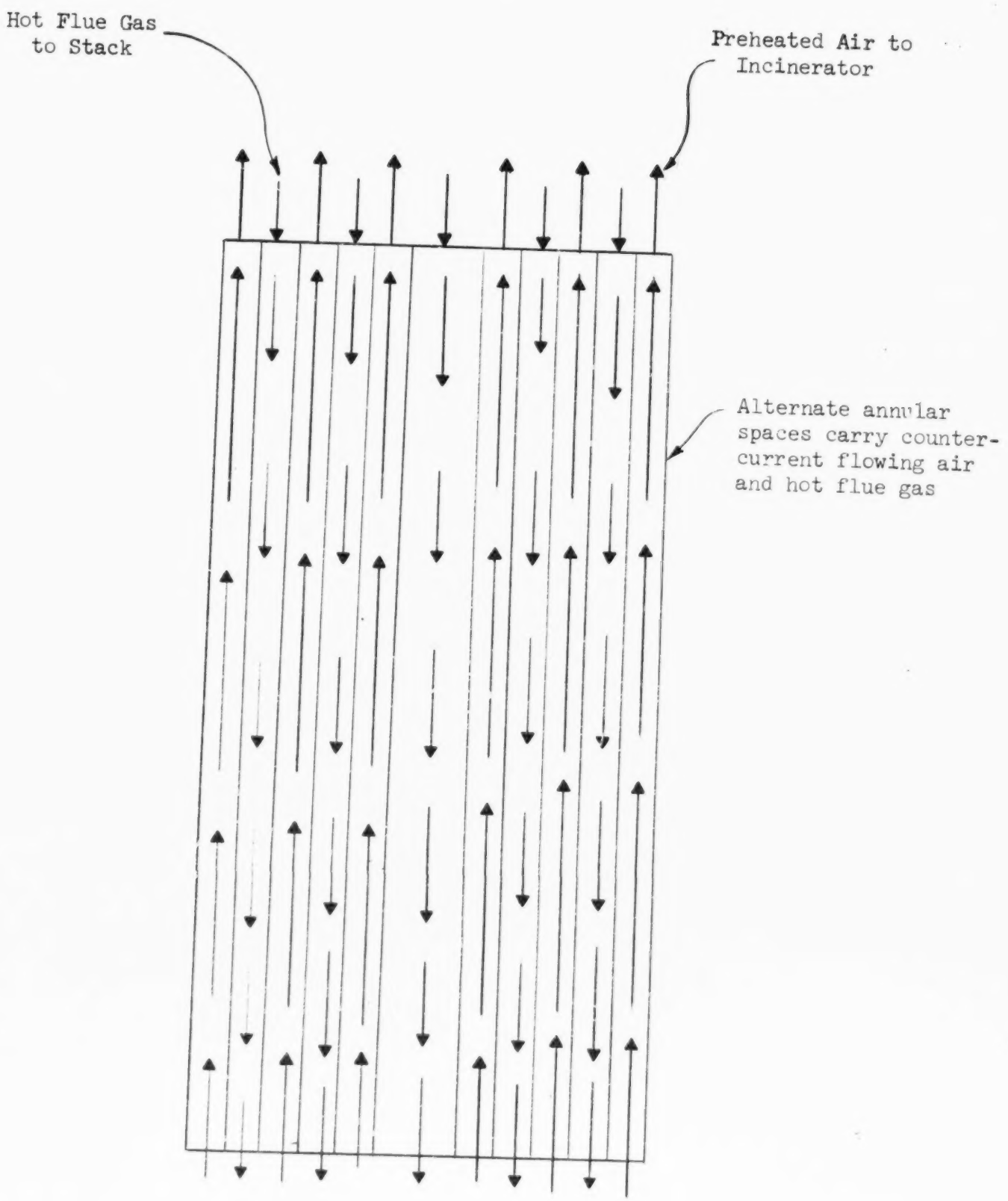

Figure 15 ANNULAR COUNTERFLOW CONCAR-TYPE AIR PREHEATER

Consulting Engineers' Fee

Based on the information described on page 26, the consulting engineers' fee is

$$CEFD = (ECD + CID)/10.0 \quad (58)$$

$$CEF = (EC + CI)/10.0 \quad (59)$$

depending on the data used for costing.

Total System Cost

The total system installed cost (TSCD or TSC) is the sum of the equipment cost, consultants' fee and installation fee

$$TSCD = ECD + CEFD + CID \quad (60)$$

$$TSC = EC + CEF + CI \quad (61)$$

Air Preheater Fuel Savings

The cost of fuel used to operate an incinerator can be reduced by the use of an air preheater. The quantity of fuel saved is directly proportional to the air preheater size thus

$$CFP = APHS\ (FC)\ (PCTY)\ (8750.0)/10^6 \quad (62)$$

represents the annual cost of fuel saved by the preheater where 8750.0 is the total hours in one year.

In the above analysis of the air preheater the maximum preheater size allowable for the system has been determined. On this basis some systems will allow the air preheater to be so large that it will cost more than the reactor and other components combined. The economics of capital cost vs. operating cost cannot be dealt with directly here because the program is not set up to evaluate this. This is so because FWPCA has planned to use this program as a subroutine. The main program is equipped to evaluate the economics required above. The exact routine to be used for evaluation of the economics will depend on the shape of the fuel cost curve (considering variable fuel cost vs. monthly usage and location). A "Do loop" which increments fuel cost along the fuel cost vs. usage curve and compares this cost to preheater cost may be the best method of cost optimization.

Annual Operating Cost

The fuel required to operate the system must supply the heat required to burn the sludge minus the heat supplied by the air preheater. Thus the cost

of fuel to operate the system for one year is

$$CF\emptyset = (QFP\ (CAP) - APHS + QLL(ZII))\ PCTY\ (8750.0)\ FC/10^6 \quad (63)$$

where 8750.0 is the total hours in one year.

Since the operating horsepower has been determined on page 25 the yearly cost of electrical power is

$$CP = \emptyset HP\ (EPC)\ (0.746)\ (PCTY)\ (8750.0) \quad (64)$$

where 0.746 is the conversion factor from horsepower to kilowatts.

Reference 1 indicates that operating labor is required for 1/4 of time that the fluidized bed incinerator operates. This agrees well with information obtained in the field. Therefore, the annual cost of operating labor for the combustion system is

$$CL = 0.25\ (CLR)\ (PCTY)\ (ZII) \quad (65)$$

The reason for sometimes using more than one incinerator is described on page 45. Also note that Equation 65 is directly related to the system PVSH because ZII is related to PVSH (see page 45). Although a man is not required full time to operate the incineration system someone must be in the general area in case of emergencies. Therefore the reported labor costs vary in different installations depending upon the work load which must be handled by the plant operators. In most cases the incinerator operators can be used for other plant operations after an initial startup period.

The annual operating cost is obtained by summing Equations 63, 64 and 65

$$C\emptyset = CF\emptyset + CP + CL \quad (66)$$

Note that this cost does not include the cost of flocculent added at the centrifuge inlet to aid coagulation. The more commonly used flocculents and dosages are listed in Table II of the field data summary.

Annual Maintenance Cost

The annual maintenance cost includes plant maintenance labor, service and repair labor, component replacement cost and sand replacement cost.

Plant maintenance labor cost is accrued because of repair work and jobs such as lubrication and sand replenishing required during the year. There was no field data available on these costs, however, the maintenance costs were stated to be quite low at all installations. It is safe to assume a maintenance cost of one man hour per day. This yields

$$CLM = (CLMR\ (PCTY)\ (8750.0)/8.0)\ (ZII) \quad (67)$$

where 8.0 reduces the cost to one eighth of a man hour for every hour of operation.

Data were not available for the cost of labor to repair instrumentation and other equipment requiring outside of plant service labor. Therefore, it was assumed that one man hour of service labor was required for each 150 hours of operation. The service labor cost is given by

$$CLMA = (CLMS\ (PCTY)\ (8750.0)/150.0)\ (ZII) \qquad (68)$$

The cost of equipment replacement was found to be very low. Most failures were in thermocouples and fuel nozzles. There was not data on these cost. Thus the expression which was assumed is

$$CER = 365.0 \qquad (69)$$

where CER = yearly cost of equipment replacement. This is equivalent to $1.00 per day of operation.

The rate of sand loss per year was defined on page 24. Sand costs about $20 per ton. Therefore, the cost of sand loss per year is

$$CSL = SLR\ (20.0)/2000.0 \qquad (70)$$

Then the annual maintenance cost is easily found as

$$CM = CLM + CLMA + CER\ (ZII) + CSL \qquad (71)$$

Annual Operating and Maintenance Cost

The total annual labor and maintenance cost is

$$TCMO = CM + CO \qquad (72)$$

Note that this cost does not include the chemical additives used to aid in dewatering the sludge.

Scrubber Costs

Table IV shows representative scrubber costs for scrubbers made by the Sly Manufacturing Company. These scrubbers were installed on some of the installations visited during this program. Scrubber costs were included in the computer program lump sum costs, but are presented here to allow reference at a future date should detailed cost data be available on other system components.

Scrubbers installed on installations visited allowed particulate emissions in the flue gases of from 0.05 to 0.75 grains per standard cubic foot of flue gas. The tolerable emission level is determined by the local air pollution laws.

TABLE IV

SLY SCRUBBER COSTS*

Two Stage Impinjet

3 GPM Water/1000 CFM (inlet) ΔP = 4.5" H_2O

Inlet[a] Gas Volume CFM	Outlet[b] Gas Volume CFM	Outside Diameter Inches	Material and Thickness			
			316 SS (3/16")	316 SS (1/8")	316 ELCSS (3/16")	316 ELCSS (1/8")
500-1,000	476	20	$ 2636	$ 2162	$ 2861	$ 2436
3,000	2,856	30	4146	3339	4479	3597
5,000	4,760	40	5897	4708	6429	5086
7,000	6,664	45	6825	5460	7410	5899
9,000	8,568	50	7969	6349	8679	6882
12,000	11,424	60	10450	8315	11318	8974

Three Stage Impinjet

24.5 GPM Water/1000 CFM (inlet) ΔP = 9" H_2O

Inlet[a] Gas Volume CFM	Outlet[c] Gas Volume CFM	Outside Diameter Inches	Material and Thickness			
			316 SS (3/16")	316 SS (1/8")	316 ELCSS (3/16")	316 ELCSS (1/8")
500-1,000	327-654	20	$ 3223	$ 2627	$ 3497	$ 2833
3,000	1,962	30	5157	4144	5558	4445
5,000	3,270	35	6311	5018	6826	5307
7,000	4,578	40	7396	5799	8003	6386
9,000	5,886	45	8725	6911	9313	7449
12,000	7,848	50	9538	7554	10400	8198

* Courtesy of Mr. Harding of Sly Manufacturing Company, Cleveland, Ohio. Costs do not include pump or surge tank.

a. Saturated @ 160°F.

b. Saturated @ 156°F.

c. Saturated @ 100°F.

Cost of Installations

A plot of the cost for fluidized bed incineration equipment (less air preheater, for primary sludge is shown in Figure 16. The assumptions made in plotting Figure 16 are that each person produces 0.2 pounds of dry solids per day. If we assume primary treatment removal of suspended solids is 60% thus 0.12 pounds of dry solids per day per person must be incinerated. Each person creates 100 gal/day of sewage water. Therefore 1 mgd is equivalent to sewage waste from 10,000 persons (1200 pounds of dry solids/day) and 100 mgd is equivalent to wastes from 1,000,000 persons.

Figure 16 shows the installed cost (less air preheater) of the fluidized bed incineration system (based on the field data curve of Figure 13) as a function of the primary treatment plant size in mgd. The assumption of an 8 hour per day burning period has been made (i.e. 1200 pounds of dry solids/day $\div$ 8 = 150 pounds of dry solids/hour). A sludge having 9000 Btu/#vs and 75% H_2O has been assumed.

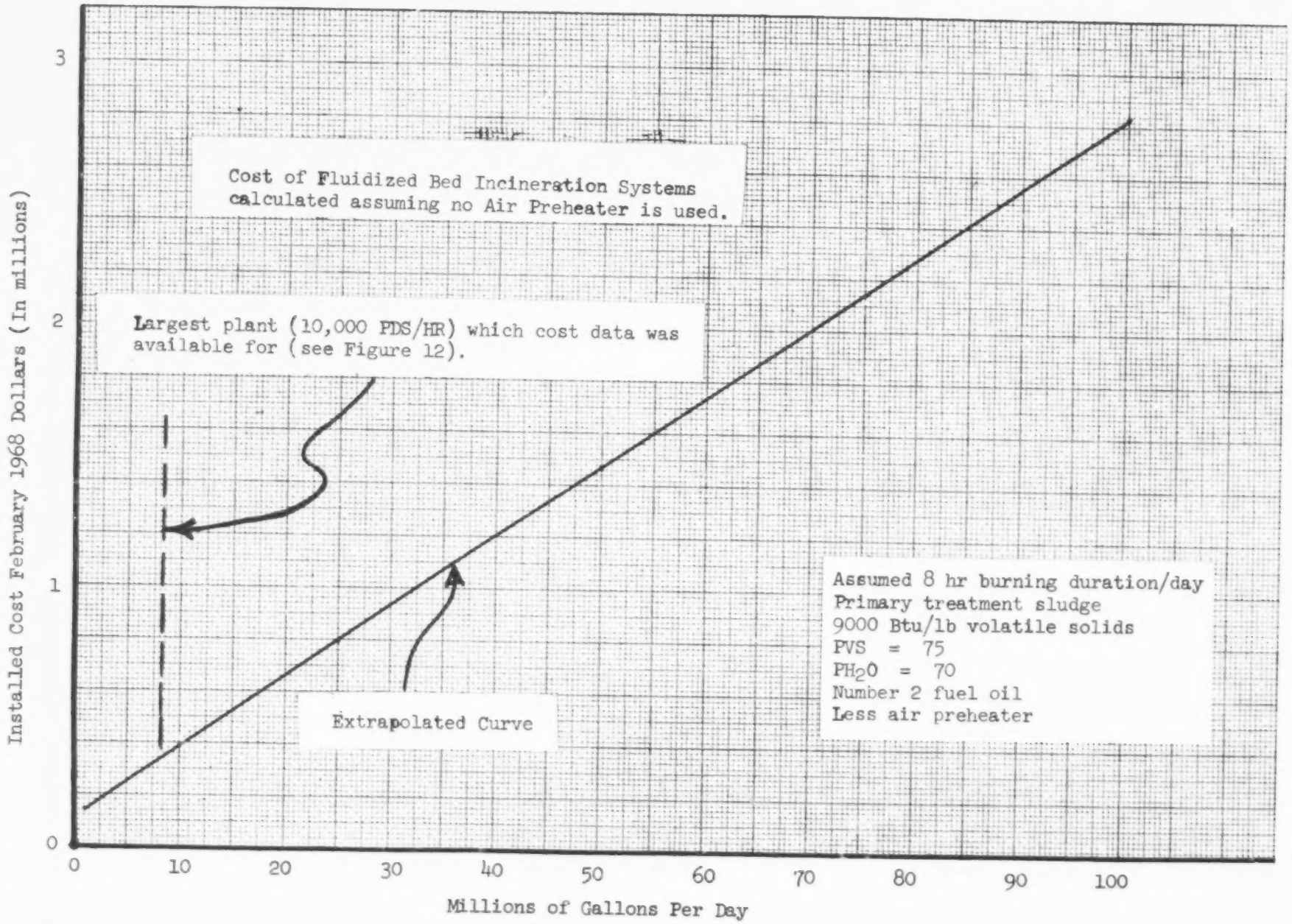

Figure 16 PLANT SIZE IN MILLION GALLONS PER DAY VS. COST

COMPUTER PROGRAM

Listing of Program

The complete program developed is listed in Fortran IV on the following pages.

```
      C     FLUIDIZED BED INCINERATION OF SEWAGE SLUDGE                       FBINC  1
            REAL NFP                                                          FBINC  2
            DIMENSION A(3),B(3),PC(3)                                         FBINC  3
        10  FORMAT(1H0,'QS=',F10.2,/,' QF=',F10.2,/,' QPE=',F10.2,/,' QLE=',F1FBINC  4
           10.2,/,' QAIR=',F10.2,/,' CAP=',F10.2,/,' PDS=',F10.2,/,' PH2O=',F1FBINC  5
           20.2,/,' PVS=',F10.2,/,' BAF=',F10.2,/,' PVSH=',F10.2,/,' PLDS=',F1FBINC  6
           30.2,/,' QFU=',F10.2)                                              FBINC  7
        11  FORMAT(1H0,'AF=',F10.2,/,' DF=',F10.2,/,' AG=',F10.2,/,' DG=',F10.FBINC  8
           12,/,' VE=',F10.2,/,' HE=',F10.2,/,' ORH=',F10.2,/,' OHP=',F10.2,/,FBINC  9
           2' NFP=',F10.2,/,' HPI=',F10.2,/,' FBHP=',F10.2,/,' HF=',F10.2)    FBINC 10
        12  FORMAT(1H0,'FC=',F10.2,/,' CLR=',F10.2,/,' CLMR=',F10.2,/,' CLMS='FBINC 11
           1,F10.2,/,' CLWR=',F10.2,/,' CSC=',F10.2,/,' CO=',F15.2,/,' CM=',F1FBINC 12
           20.2,/,' CP=',F15.2,/,' CFO=',F15.2,/,' APHC=',F10.2,/,' EPC=',F10.FBINC 13
           32,/,' CEF=',F10.2,/,' CEFD=',F10.2,/,' EC=',F10.2,/,' ECD=',F10.2,FBINC 14
           4/,' CFP=',F10.2,/,' COR=',F10.2,/,' CORD=',F10.2,/,' CI=',F10.2,/,FBINC 15
           5' CID=',F10.2,/,' TSC=',F10.2,/,' TSCD=',F10.2)                   FBINC 16
        13  FORMAT(1H0,'TA=',F10.2,/,' TW=',F10.2,/,' PAPH=',F10.2,/,' SLR=',FFBINC 17
           110.2,/,' QSL=',F10.2)                                             FBINC 18
        14  FORMAT(1H0,'ASSUMED PROGRAMMED SLUDGE ELEMENTAL COMPOSITION')     FBINC 19
        15  FORMAT(1H0,'READ SLUDGE ELEMENTAL COMPOSITION')                   FBINC 20
        16  FORMAT(1H0,'NATURAL GAS FUEL')                                    FBINC 21
        17  FORMAT(1H0,'NO.2 FUEL OIL')                                       FBINC 22
        18  FORMAT(1H0,'WATER QUENCH MAY BE REQD. IN REACTOR')                FBINC 23
        19  FORMAT(1H0,'PILOT PLANT DATA')                                    FBINC 24
        20  FORMAT(1H0,'CALC QF,BAF,QPE=0,QLE=0')                             FBINC 25
        21  FORMAT(1HI,'CASE',I3)                                             FBINC 26
        22  FORMAT(1H0,'SYSTEM IS TOO SMALL TO BE COSTED BY DORR CURVES ',/,' FBINC 27
           1AN ESTIMATE IS GIVEN BY FIELD DATA EQUATIONS',/,' ANY DATA PRINTEDFBINC 28
           2 FOR CORD,CEFD,ECD,CID,TSCD, SHOULD BE DISREGARDED')             FBINC 29
        23  FORMAT(13F6.0)                                                    FBINC 30
        24  FORMAT(13F6.2)                                                    FBINC 31
        25  FORMAT(6F12.8)                                                    FBINC 32
        26  FORMAT(3I1)                                                       FBINC 33
            NWO                                                               FBINC 34
       100  READ(2,23  ) QS,QFU,CAP,TA,TW,CLR                                 FBINC 35
            READ(2,24  ) PC,PCT,PP,STEPC,CLR,CLMR,CLMS,PH2O                   FBINC 36
            READ(2,26  )LITE,LIT,LII                                          FBINC 37
            N=1                                                               FBINC 38
            WRITE(3,21  ) N                                                   FBINC 39
            GO TO ( 110, 120),LITE                                            FBINC 40
       110  READ(2,23  ) QF,QPE,QLE,BAF                                       FBINC 41
            WRITE(3,19  )                                                     FBINC 42
            GO TO  270                                                        FBINC 43
       120  FW=0.0                                                            FBINC 44
            I=0                                                               FBINC 45
            WRITE(3,20  )                                                     FBINC 46
            QPE=0.0                                                           FBINC 47
            QLE=0.0                                                           FBINC 48
            GO TO ( 130, 140),LIT                                             FBINC 49
       130  A(1)=.0458                                                        FBINC 50
            B(1)=.037                                                         FBINC 51
            C=.010438                                                         FBINC 52
            D=.001107                                                         FBINC 53
            WRITE(3,14  )                                                     FBINC 54
            GO TO  150                                                        FBINC 55
       140  READ(2,25  )A(1),B(1),C,D                                         FBINC 56
            WRITE(3,15  )                                                     FBINC 57
            A(1)=A(1)/12.                                                     FBINC 58
            B(1)=B(1)/2.                                                      FBINC 59
            C=C/32.                                                           FBINC 60
```

```
      D=D/28.                                                          FBINC 61
  150 GO TO ( 160, 170),LIT                                            FBINC 62
  160 A(2)=1.                                                          FBINC 63
      B(2)=2.                                                          FBINC 64
      WRITE(3,16  )                                                    FBINC 65
      GO TO  180                                                       FBINC 66
  170 A(2)=1.2                                                         FBINC 67
      B(2)=1.                                                          FBINC 68
      WRITE(3,17  )                                                    FBINC 69
  180 POVS=12.*A(1)+2.*B(1)+32.*C+28.*D                                FBINC 70
      PDSC=POVS/(PVS/100.)                                             FBINC 71
      PS=100.*PDSC/(100.-PH2O)                                         FBINC 72
      PPH2O=PS-PDSC                                                    FBINC 73
      SCP=PS*60.                                                       FBINC 74
      QSL=QS*POVS/PS                                                   FBINC 75
  190 A(3)=A(1)+FM*A(2)                                                FBINC 76
      B(3)=B(1)+FM*B(2)                                                FBINC 77
      XF=(A(3)+B(3)/2.-C)                                              FBINC 78
      IF(XF) 200,210,210                                               FBINC 79
  200 XF=0.                                                            FBINC 80
  210 PVT=A(3)+B(3)+D+3.76*XF+PPH2O/18.                                FBINC 81
      Y=.04*PVT/.8096                                                  FBINC 82
      PV4T=PVT+4.76*Y                                                  FBINC 83
      CPC2O=A(3)*18200.                                                FBINC 84
      CPH2O=(B(3)+PPH2O/18.)*14000.                                    FBINC 85
      CP2N=3.76*(XF+Y1+D)*28.*.279*1400.                               FBINC 86
      CP2O=Y*11800.                                                    FBINC 87
      CPIN=(PDSC-POVS)*336.                                            FBINC 88
      SUMQ=CPC2O+CPH2O+CP2N+CP2O+CPIN                                  FBINC 89
      THCP=SUMQ/PS                                                     FBINC 90
      AIRCP=(XF+Y)*1980.                                               FBINC 91
      THCPT=QSL*(QFU*FN*112.*A(2)*2.*B(2))+AIRCP*SCP)/PS               FBINC 92
      SUM=THCP-THCPT                                                   FBINC 93
      I=I+1                                                            FBINC 94
      IF(I-1) 230,230,220                                              FBINC 95
  220 IF(SUM) 260,260,250                                              FBINC 96
  230 IF(SUM) 240,260,250                                              FBINC 97
  240 WRITE(3,18  )                                                    FBINC 98
      GO TO  260                                                       FBINC 99
  250 FM=FM+.001                                                       FBINC100
      GO TO  190                                                       FBINC101
  260 QF=FM*(A(2)*12.+B(2)*2.)*QFU/PS                                  FBINC102
      BAF=137.5*(XF+Y)/PS                                              FBINC103
  270 PI=3.14159                                                       FBINC104
      QAIR=15.*BAF                                                     FBINC105
      QE=QSL+QF+QPE+QAIR-QLG                                           FBINC106
      QFP=QF+QPE                                                       FBINC107
      IF(QFP) 380,380,280                                              FBINC108
  280 CF=FC*QFP*PCTY*(8750.)*CAP/10.**6                                FBINC109
      PC(1)=QE*CAP*.71428                                              FBINC110
      PC(2)=BAF*.24*(1000.-60.)*CAP                                    FBINC111
      IF(PC(1)-PC(2)) 290,290,300                                      FBINC112
  290 PC(3)=PC(1)                                                      FBINC113
      GO TO  310                                                       FBINC114
  300 PC(3)=PC(2)                                                      FBINC115
  310 DQ=QFP-PC(3)                                                     FBINC116
      IF(QFP-PC(3)) 320,330,330                                        FBINC117
  320 ARMS=QFP*CAP                                                     FBINC118
      GO TO  340                                                       FBINC119
  330 ARMS=PC(3)                                                       FBINC120
```

```
      340 APHC=(2.9*APHS/60.)
          IF(APHC)  350,350,360                                          FBINC121
      350 APHC=0.                                                        FBINC122
      360 CFP=APHS*FC*PCFY*8750.7(10.**6                                 FBINC123
          IF(CFP) 370,370,390                                            FBINC124
      370 CFP=0.                                                         FBINC125
          GO TO  390                                                     FBINC126
      380 PC(3)=0.0                                                      FBINC127
          CFP=0.                                                         FBINC128
          APHC=0.                                                        FBINC129
      390 PCDS=(100.-PH20)                                               FBINC130
          PDS=CAP*PCDS/100.                                              FBINC131
          PVSH=PDS*PVS/100.                                              FBINC132
          IF(PVSH-1500.) 430,430,400                                     FBINC133
      400 ZII=2.                                                         FBINC134
      410 ZI=PVSH/ZII                                                    FBINC135
          IF(ZI-1500.) 440,440,420                                       FBINC136
      420 ZII=ZII+1.                                                     FBINC137
          GO TO  410                                                     FBINC138
      430 ZI=PVSH                                                        FBINC139
          ZII=1.                                                         FBINC140
      440 QL=400.0                                                       FBINC141
          PDSI=PDS*ZI/PVSH                                               FBINC142
      450 SUMQ=((QSL+QFP)*CAP)/ZII+QL                                    FBINC143
          AG=SUMQ/155000.                                                FBINC144
          AF=AG/(0.985-0.306*((PH20/100.)**2-0.999*(PH20/100.)**4.))     FBINC145
          VE=SUMQ/18000.                                                 FBINC146
          HE=VE/(1.047*(AF/PI+SQRT(AF/PI)*SQRT(AG/PI)+AG/PI))            FBINC147
          DG=SQRT(4.0*AG/PI)                                             FBINC148
          DF=SQRT(4.0*AF/PI)                                             FBINC149
          VS=VE/1.5                                                      FBINC150
          HF=1.6*HE                                                      FBINC151
          PV=SUMQ*2.5/10.**5                                             FBINC152
          HP=PV/AG                                                       FBINC153
          AO=PI*(HF*DF+HE*(DF+DG)/2.0)                                   FBINC154
          QLL=4.0*AO*(TW-TA)                                             FBINC155
          IF(QLL-QL) 470,470,460                                         FBINC156
      460 QL=QL+2000.                                                    FBINC157
          GO TO  450                                                     FBINC158
      470 ORH=HP+HE+HF                                                   FBINC159
          NFP=FLOAT(IFIX(100.0*PDSI/(2000.*PCDS)+0.500001))              FBINC160
          IF(NFP) 480,480,490                                            FBINC161
      480 NFP=1.0                                                        FBINC162
      490 CONTINUE                                                       FBINC163
          IF(PCDS-31.) 500,500,510                                       FBINC164
      500 CORD=110.**(1.7/(1.14+.434294482*ALOG(PDSI-1.64771)*100.*PDS   FBINC165
          GO TO  520                                                     FBINC166
      510 CORD=110.**(1.7/(2.10+.434294482*ALOG(PDSI-4.38111)*100.*PDS   FBINC167
      520 COR=100000.+212.*PVSH                                          FBINC168
          HPII=19.2-.01024*ZI+.0001607*(ZI)**2                           FBINC169
          FBHPI=-5.68+.90*HPII-.000565*((HPII)**2)                       FBINC170
          OHP1=.625*HPII                                                 FBINC171
          HPI=HPII*ZII                                                   FBINC172
          FBHP=FBHPI*ZII                                                 FBINC173
          OHP=OHPI*ZII                                                   FBINC174
          EC=COR*APHC                                                    FBINC175
          ECD=CORD+APHC                                                  FBINC176
          CI=EC/10.                                                      FBINC177
          CID=ECD/10.                                                    FBINC178
          CEP=(EC-CI)/10.                                                FBINC179
                                                                         FBINC180
```

```
      CEFD=(ECD+CID)/10.                                                FBINC181
      PAPH=PDS*PVSH                                                     FBINC182
      CL=0.25*CLR*PCTY*ZII                                              FBINC183
      CP=OHP*EPC*.746*PCTY*8750.                                        FBINC184
      CFO=(GFP*CAP-APHS+QLL*ZIII*PCTY*8750.*FC/10.**6                   FBINC185
      IF(CFO) 530,530,540                                               FBINC186
  530 CFO=0.                                                            FBINC187
  540 CO=CL+CP+CFO                                                      FBINC188
      IF((DF/HF)-.64) 550,550,560                                       FBINC189
  550 GLR=(.32*DF*PCTY*8750./(30.*HF*8.))*ZII                           FBINC190
      GO TO  570                                                        FBINC191
  560 GLR=10350.*((DF/HF-.6)*PCTY*30.45)*ZII                            FBINC192
  570 CLM=CLMR*PCTY*1093.7*ZII                                          FBINC193
      CLMA=CLMS*PCTY*50.33*ZII                                          FBINC194
      CSL=GLR/100.                                                      FBINC195
      CM=CLM+CLMA+CSL+365.*ZII                                          FBINC196
      TCMO=CM+CO                                                        FBINC197
      TSC=EC+CEF+CI                                                     FBINC198
      TSCD=ECD+CEFD+CID                                                 FBINC199
      CAPI=CAP/ZII                                                      FBINC200
      WRITE(3,10  ) QS,QF,QPE,QLE,QAIR,CAP,PDS,PH2O,PVS,BAF,PVSH,PCDS,QFFBINC201
     1D                                                                 FBINC202
      WRITE(3,11  ) AF,DF,AG,DG,VE,HE,ORH,OHP,NFP,HPI,FBHP,HF          FBINC203
      IF(PDS-400.) 580,590,590                                          FBINC204
  580 WRITE(3,22  )                                                     FBINC205
  590 WRITE(3,12  ) FC,CLR,CLMR,CLMS,CLMA,CSL,CO,CM,CP,CFO,APHS,EPC,CEF,FBINC206
     1CEFD,EC,ECD,CFP,COR,CORD,CI,CID,TSC,TSCD                          FBINC207
      WRITE(3,13  ) TA,TW,PAPH,SLR,GSL                                  FBINC208
      WRITE(3,23)PV4T                                                   FBINC209
      PAUSE 1111                                                        FBINC210
      CALL DATSW(4,MORE)                                                FBINC211
      GO TO (-100,-600),MORE                                            FBINC212
  600 CALL EXIT                                                         FBINC213
      END                                                               FBINC214
```

Flow Chart

The flow chart for the computer program developed is shown in Figure 17.

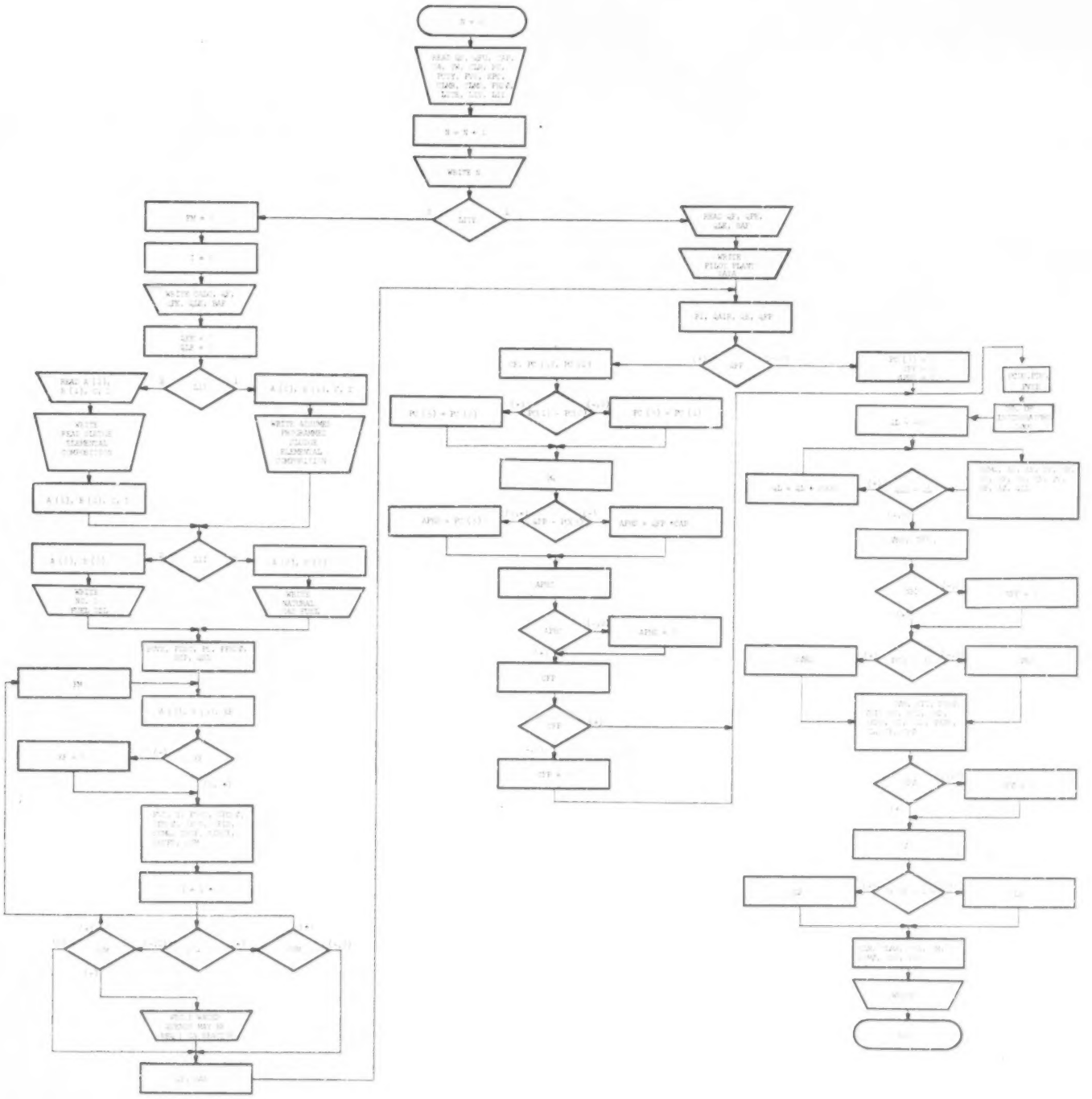

Figure 17 FLOW CHART OF COMPUTER PROGRAM

How to Use The Computer Program

Options in the Selection of Input Data

The program is set up to follow different loops depending on the index values read in. The options available are:

1) The use of pilot plant data for fuel and air requirements or the use of the calculation routine for these variables set up in the program.

2) The use of the programmed sludge chemical composition or an input sludge chemical composition for calculation of the variables in 1 above.

3) The use of natural gas or Number 2 fuel oil in the calculation of 1 above.

In the use of option 2 above the operator should note that the programmed sludge composition is a representative value based on Reference 2. The errors involved in using this routine instead of pilot data are that the assumption must be made that the sludge exists in an unoxidized state. Therefore, the oxidation reactions would be

$$2\,H_2 + \emptyset_2 \longrightarrow 2\,H_2\emptyset$$

$$C + \emptyset_2 \longrightarrow C\emptyset_2$$

However, the sludge consists of compounds in a partially oxidized state, for example the combustion reactions

$$C\emptyset + \frac{\emptyset_2}{2} \longrightarrow C\emptyset_2$$

$$C\emptyset_X + Y\emptyset_2 \longrightarrow C\emptyset_2$$

$$H\emptyset + Z\emptyset_2 \longrightarrow H_2O$$

$$H\emptyset_X + K\emptyset_2 \longrightarrow H_2O$$

may occur instead of the complete combustion reactions shown above. Thus the difficulty and inaccuracy of determining the fuel and air requirements needed to support sludge combustion is apparent. Because of this limitation it is advisable to use pilot plant data when accurate results are required.

No assumptions can be made as to the accuracy of calculations when the programmed sludge elemental composition is assumed. The insertion of a true elemental composition for the sludge of interest, with a corresponding sludge heating value (QS) may yield a more accurate analysis.

Reactor Sizing Limit

As with any mechanical equipment, there is a maximum tolerable size above which a fluidized bed incinerator cannot be economically constructed. The physical size and operating stress combine to make this limit apparently a unit with a design capacity of 1500 pounds of volatile solids per hour or a reactor freeboard diameter of 16 to 17 feet (based on Kansas City units). Therefore, when a system with a higher capacity than 1500# VS/HR and/or a greater freeboard diameter than 16 feet is required, the system should be split into two or more systems of equal size (i.e., PVS/2, PVS/3, etc.) if it is to be handled by this program. This is done in the computer program and ZII is used to represent the number of incineration reactors having a volatile solids capacity of 1500#/hr or less. The computed capacity of each reactor is ZI. The system cost curves are defined to 10,000# dry solids/hr (Figure 12). Accuracy beyond this capacity is uncertain and the computer program usage should be limited to capacities below the above.

Air Preheater Option

The decision to use an air preheater can only be made through an economic analysis which FWPCA has set up in the executive program. Since this program will be used as a subroutine for this executive program, no attempt was made to optimize the system. The air preheater is sized based on the required system heat requirement from fuel and the preheater. The maximum preheater capacity for each reactor vessel is given by

$$APHSI = APHS/ZII \tag{73}$$

To optimize the air preheater size, a trade-off between fuel costs and air preheater size must be accomplished in the executive program.

Data Input and Output

Figures 18, 19 and 20 show the input cards used to obtain the data for Figure 16. The output data from the computer program for each set of data input are shown respectively in Figures 21 through 32.

To obtain this data, two cards

APHC = 0.0

APHS = 0.0

were inserted after card FBINC121 in the program listing shown in this report. This was done simply to eliminate the air preheater, since the cost optimization needed from the executive program to aid in sizing the preheater, is not included in this subroutine.

The indices used for program control on Card 3 are described below:

1) LITE = 1 when pilot plant data are used for QF, QPE, QLE, BAF,
   LITE = 2 when QF, BAF are unknown.
2) LIT = 1 when sludge elemental composition is known from tests,
   LIT = 2 when sludge elemental composition is unknown.
3) LII = 1 when using natural gas fuel,
   LII = 2 when using #2 fuel oil.

CARD #1 QS, QFU, CAP, TA, TW, CLR
CARD #2 FC, PCTY, PVS, EPC, CLMR, CLMS, PH2Ø
CARD #3 LITE, LIT, LII

```
9000.10000.  500.   60.  200. 5000.
  1.33   .24 70.      .03  3.    8.    70.
212
```

C FOR COMMENT | STATEMENT NUMBER | CONTINUATION | FORTRAN STATEMENT | IDENTIFICATION

BSC 68815?

Data Cards Case 1

```
9000.10000. 5000.   60.  200. 5000.
  1.33   .24 70.      .03  3.    8.    70.
212
```

C FOR COMMENT | STATEMENT NUMBER | CONTINUATION | FORTRAN STATEMENT | IDENTIFICATION

BSC 68815?

Data Cards Case 2

Figure 18 DATA CARDS

```
9000.10000.12500.   60.  200. 5000.
C FOR COMMENT
   1.33   .24 70.      .03  3.    8.   70.
C FOR COMMENT
212
C FOR COMMENT
STATEMENT NUMBER | CONTINUATION | FORTRAN STATEMENT | IDENTIFICATION
```

BSC 888157

Data Cards Case 3

```
9000.10000.25000.   60.  200. 5000.
C FOR COMMENT
   1.33   .24 70.      .03  3.    8.   70.
C FOR COMMENT
212
C FOR COMMENT
STATEMENT NUMBER | CONTINUATION | FORTRAN STATEMENT | IDENTIFICATION
```

BSC 888157

Data Cards Case 4

Figure 19 DATA CARDS

```
9000.10000.37500.    60.   200. 5000.
C-- FOR COMMENT
   1.33   .24 70.      .03  3.    8.    70.
C-- FOR COMMENT
212
C-- FOR COMMENT
STATEMENT NUMBER | CONTINUATION | FORTRAN STATEMENT | IDENTIFICATION
```

BSC 888157

Data Cards Case 5

```
9000.10000.50000.    60.   200. 5000.
C-- FOR COMMENT
   1.33   .24 70.      .03  3.    8.    70.
C-- FOR COMMENT
212
C-- FOR COMMENT
STATEMENT NUMBER | CONTINUATION | FORTRAN STATEMENT | IDENTIFICATION
```

BSC 888157

Data Cards Case 6

Figure 20 DATA CARDS

```
CASE  I
CALC QF,BAF,QPE=0,QLE=0
ASSUMED PROGRAMMED SLUDGE ELEMENTAL COMPOSITION
NO.2 FUEL OIL
WATER QUENCH MAY BE REQD. IN REACTOR
   QS=    9000.00
   QF=       0.00
  QPE=       0.00
  QLE=       0.00
 QAIR=      33.76
  CAP=     500.00
  PDS=     150.00
 PH2O=      70.00
  PVS=      70.00
  BAF=       2.25
 PVSH=     105.00
 PCDS=      30.00
  QFU=   10000.00

   AF=       7.94
   DF=       3.18
   AG=       6.83
   DG=       2.94
   VE=      58.85
   HE=       7.97
  ORH=      24.60
  OHP=       9.93
  NFP=       1.00
  HPI=      15.89
 FBHP=       8.48
   HF=      12.75

SYSTEM IS TOO SMALL TO BE COSTED BY DORR CURVES
AN ESTIMATE IS GIVEN BY FIELD DATA EQUATIONS
ANY DATA PRINTED FOR CORD,CEFD,ECD,CID,TSCD, SHOULD BE DISREGARDED

   FC=       1.33
  CLR=    5000.00
 CLMR=       3.00
 CLMS=       8.00
 CLMA=     111.99
  CSL=      13.79
   CO=          1086.39
   CM=    1278.24
   CP=           466.94
  CFO=           319.45
 APHC=       0.00
  EPC=       0.03
  CEF=   13448.60
 CEFD=   25521.57
   EC=  122260.01
  ECD=  232014.37
  CFP=       0.00
  COR=  122260.01
```

Figure 21 SAMPLE DATA

```
 CORD= 232014.37
 CI=  12226.00
 CID=  23201.43
 TSC= 147934.62
 TSCD= 280737.37

 TA=      60.00
 TW=     200.00
 PAPH=     45.00
 SLR=   1379.19
 QSL=   1890.00
   0.
```

Figure 22 SAMPLE DATA

```
 CASE  2

 CALC QF,BAF,QPE=0,QLE=0

 ASSUMED PROGRAMMED SLUDGE ELEMENTAL COMPOSITION

 NO.2 FUEL OIL

 WATER QUENCH MAY BE REQD. IN REACTOR

 QS=   9000.00
 QF=      0.00
 QPE=     0.00
 QLE=     0.00
 QAIR=   33.76
 CAP=  5000.00
 PDS=  1500.00
 PH2O=    70.00
 PVS=     70.00
 BAF=      2.25
 PVSH=  1050.00
 PCDS=    30.00
 QFU=  10000.00

 AF=     73.50
 DF=      9.67
 AG=     63.21
 DG=      8.97
 VE=    544.35
 HE=      7.97
 ORH=    24.60
 OHP=   113.51
 NFP=     3.00
 HPI=   181.61
 FBHP=  139.14
 HF=     12.75

 FC=      1.33
 CLR=  5000.00
 CLMR=    3.00
 CLMS=    8.00
 CLMA=  111.99
 CSL=   143.49
 CO=     6606.37
 CM=    1407.95
 CP=     5334.84
 CFO=     971.52
 APHC=    0.00
 EPC=     0.03
 CEF=  35486.00
 CEFD=  52764.88
 EC= 322600.06
 ECD= 479680.81
 CFP=     0.00
 COR= 322600.06
 CORD= 479680.81
 CI=  32260.00
 CID=  47968.07
 TSC= 390346.06
```

Figure 23 SAMPLE DATA

```
TSCD= 380413.75
 TA=      60.00
 TW=     200.00
 PAPH=    450.00
 SLR=   14349.66
 QSL=   1890.00
    0.
```

Figure 24 SAMPLE DATA

```
CASE  3
CALC QF,BAF,QPE=0,QLE=0
ASSUMED PROGRAMMED SLUDGE ELEMENTAL COMPOSITION
NO.2 FUEL OIL
WATER QUENCH MAY BE REQD. IN REACTOR

QS=     9000.00
QF=        0.00
QPE=       0.00
QLE=       0.00
QAIR=     33.76
CAP=   12500.00
PDS=    3750.00
PH2O=     70.00
PVS=      70.00
BAF=       2.25
PVSH=   2625.00
PCDS=     30.00
QFU=   10000.00

AF=       91.53
DF=       10.79
AG=       78.71
DG=       10.01
VE=      677.82
HE=        7.97
ORH=      24.60
OHP=     348.23
NFP=       3.00
HPI=     557.18
FBHP=    402.40
HF=       12.75

FC=        1.33
CLR=    5000.00
CLMR=      3.00
CLMS=      8.00
CLMA=    223.98
CSL=     446.15
CO=        19134.72
CM=     2975.07
CP=        16366.50
CFO=        2158.22
APHC=      0.00
EPC=       0.03
CEF=   72215.01
CEFD=  106219.37
EC=  656500.12
ECD=  965630.75
CFP=       0.00
COR=  656500.12
CORD=  965630.75
CI=   65650.01
CID=   96563.07
TSC=  794365.12
```

Figure 25 SAMPLE DATA

```
TSCD=1168413.25
 TA=     60.00
 TW=    200.00
PAPH=   1125.00
SLR=   44615.71
QSL=    1890.00
   0.
```

Figure 26 SAMPLE DATA

```
 CASE  4
 CALC QF,BAF,QPE=0,QLE=0
 ASSUMED PROGRAMMED SLUDGE ELEMENTAL COMPOSITION
 NO.2 FUEL OIL
 WATER QUENCH MAY BE REQD. IN REACTOR
 QS=    9000.00
 QF=       0.00
 QPE=      0.00
 QLE=      0.00
 QAIR=    33.76
 CAP=   25000.00
 PDS=    7500.00
 PH2O=     70.00
 PVS=      70.00
 BAF=       2.25
 PVSH=   5250.00
 PCDS=     30.00
 QFU=   10000.00

 AF=       91.53
 DF=       10.79
 AG=       78.71
 DG=       10.01
 VE=      677.82
 HE=        7.97
 ORH=      24.60
 OHP=     696.47
 NFP=       3.00
 HPI=    1114.36
 FBHP=    804.80
 HF=       12.75

 FC=        1.33
 CLR=    5000.00
 CLMR=      3.00
 CLMS=      8.00
 CLMA=    447.97
 CSL=     892.31
 CO=        38269.45
 CM=    5950.14
 CP=        32733.01
 CFO=        4336.44
 APHC=      0.00
 EPC=       0.03
 CEF= 133430.03
 CEFD= 189068.40
 EC=1213000.25
 ECD=1718258.25
 CFP=       0.00
 COR=1213000.25
 CORD=1718258.25
 CI= 121300.01
 CID= 171825.81
 TSC=1467730.25
```

Figure 27 SAMPLE DATA

```
TSCD=2079092.25
TA=      60.00
TW=     200.00
PAPH=   2250.00
SLR=   89231.42
QSL=    1890.00
   0.
```

Figure 28 SAMPLE DATA

```
 CASE  5
 CALC QF,BAF,QPE=0,QLE=0
 ASSUMED PROGRAMMED SLUDGE ELEMENTAL COMPOSITION
 NO.2 FUEL OIL
 WATER QUENCH MAY BE REQD. IN REACTOR
 QS=    9000.00
 QF=       0.00
 QPE=      0.00
 QLE=      0.00
 QAIR=    33.76
 CAP=   37500.00
 PDS=   11250.00
 PH2O=     70.00
 PVS=      70.00
 BAF=       2.25
 PVSH=   7875.00
 PCDS=     30.00
 QFU=   10000.00
 AF=      91.53
 DF=      10.79
 AG=      78.71
 DG=      10.01
 VE=     677.82
 HE=        7.97
 ORH=      24.60
 OHP=    1044.71
 NFP=       3.00
 HPI=    1671.54
 FBHP=    1207.20
 HF=      12.75
 FC=       1.33
 CLR=    5000.00
 CLMR=        3.00
 CLMS=        8.00
 CLMA=      671.96
 CSL=    1338.47
 CO=       57404.16
 CM=    8925.21
 CP=       49099.50
 CFO=        6504.66
 APHC=       0.00
 EPC=        0.03
 CEF= 194645.03
 CEFD= 268105.56
 EC=1769500.25
 ECD=2437323.50
 CFP=        0.00
 COR=1769500.25
 CORD=2437323.50
 CI= 176950.03
 CID= 243732.31
 TSC=2141095.50
```

Figure 29 SAMPLE DATA

```
 TSCD=2949161.00
 TA=      60.00
 TW=     200.00
 PAPH=   3375.00
 SLR= 133847.12
 QSL=    1890.00
    0.
```

Figure 30 SAMPLE DATA

```
CASE  6
CALC QF,BAF,QPE=0,QLE=0
ASSUMED PROGRAMMED SLUDGE ELEMENTAL COMPOSITION
NO.2 FUEL OIL
WATER QUENCH MAY BE REQD. IN REACTOR
QS=    9000.00
QF=       0.00
QPE=      0.00
QLE=      0.00
QAIR=    33.76
CAP=   50000.00
PDS=   15000.00
PH2O=     70.00
PVS=      70.00
BAF=       2.25
PVSH=  10500.00
PCDS=     30.00
QFU=   10000.00

AF=     104.40
DF=      11.52
AG=      89.78
DG=      10.69
VE=     773.13
HE=       7.97
ORH=     24.60
OHP=   1581.19
NFP=      4.00
HPI=   2529.90
FBHP=  1720.54
HF=      12.75

FC=       1.33
CLR=   5000.00
CLMR=        3.00
CLMS=        8.00
CLMA=      783.95
CSL=    1926.27
CO=        84517.48
CM=    10777.47
CP=        74312.75
CFO=        8104.73
APHC=       0.00
EPC=        0.03
CEF=  255860.03
CEFD=  345080.56
EC=2326000.50
ECD=3137096.00
CFP=        0.00
COR=2326000.50
CORD=3137096.00
CI=  232600.03
CID=  313709.56
TSC=2814460.50
```

Figure 31 SAMPLE DATA

```
 TSCD=3795886.00
   TA=      60.00
   TW=     200.00
 PAPH=    4500.00
  SLR=  192627.31
  QSL=    1890.00
     0.
```

Figure 39 SAMPLE DATA

CONCLUSIONS AND RECOMMENDATIONS

Performance of the System

The personnel at all of the installations visited were very well pleased with the performance of the fluidized bed incineration system. Most operating problems appeared to be caused by jamming feed systems. Both the special retractable screw feed (Patent, Reference 3) and the screw pump-flexible line feed system were subject to occasional jamming because of overdrying of the sludge feed at the incinerator or because of silt carried into the feed system with the sludge. The only other frequently occurring problems appeared to be the burnout of spray nozzles or thermocouples in the bed.

The fluidized bed incinerator is uniquely qualified for applications where liquified wastes having insufficient heating value or variable heating value must be disposed of. The height of the freeboard determines the sand loss rate. This is a variable and should be stated with any price quotation.

Method of Rating

All of the fluidized bed incinerator contracts reviewed at FWPCA offices had a performance specification sheet which was supplied by the manufacturer (Dorr-Oliver) of the incineration system. These specification sheets were seldom filled out to allow an adequate verification of any performance guarantee.

Further, it was found that the method of verifying that the systems met the contract specifications on capacity was totally inadequate. The method uses an empirical relationship of 1 standard cubic foot of air equals 100 BTU at stoichiometric conditions. Therefore, the claim that the sludge burning capacity of the incinerator can be measured by simply measuring the air flow is in error. The discrepancy is apparent when one considers that H_2 requires 1/2 mole of $\emptyset_2$ while C require 1 mole of $\emptyset_2$ for complete combustion. However, H_2 produces about 64,000 Btu/# and C produces only 16,000 Btu/# when completely burned. The ratio of Btu's produced to air requirements for H_2 in standard cubic feet is thus

$$\frac{64{,}000 \text{ Btu/\#}H_2 \left(\frac{2 \text{ \# } H_2}{\text{mole } H_2O}\right)}{4.76 \text{ (1/2 mole } \emptyset_2\text{) moles air}} = 53{,}700 \text{ Btu/mole air}$$

One mole of air has a volume at standard conditions of 378 ft^3. Therefore,

$$53{,}700 \text{ Btu/mole air } \left(\frac{1 \text{ mole}}{378 \text{ std. } ft^3 \text{ air}}\right) = 142 \text{ Btu/SCF air}$$

The ratio for C is

$$\frac{12{,}000 \text{ Btu/\#C } \left(\frac{12\text{\# C}}{\text{mole C}\emptyset_2}\right)}{4.76 \text{ (1mole } \emptyset_2\text{) moles air}} = 30{,}200 \text{ Btu/mole air}$$

Therefore,

$$30{,}200 \text{ Btu/mole air } \left(\frac{1 \text{ mole air}}{378 \text{ std ft}^3 \text{ air}}\right) = 80 \text{ Btu/SCF air}$$

Thus, it is seen that the air requirement per Btu of heating value of sludge or any other fuel will vary significantly from a standard of 100 Btu/Std ft^3 air. It is therefore recommended that another method (such as sludge weighing) be used for evaluation of the burning capacity of an incinerator during acceptance testing.

Factors Influencing Operating Costs

The effectiveness of the dewatering system plays an important part in determining the fuel requirements for a sludge incineration system. A system with a good dewatering device, of sufficiently low power requirements, can greatly reduce the fuel requirements. At all plants visited, chemicals were added to the sludge prior to the dewatering device. The cost of the chemicals required was not clearly spelled out in any contract reviewed on this project. Also,the contracts failed to require any guarantee on fuel consumption or power consumption because of the lack of data supplied in the contracts. The contract sheets requiring this data were left blank in all cases. The cost of operation in dollars per pound of volatile solids should be clearly spelled out in any such contract.

Accuracy of the Equations Developed

The equations developed on this program were based on the most accurate information attainable from the field. There were significant variations in system design from one plant to another.

The costs for the units surveyed did not follow the costs submitted to FWPCA (Reference 1). In most cases, the actual prices paid for the units surveyed were significantly below the manufacturer's (Reference 1). As competition from other manufacturers increases, the prices probably will be reduced below the prices now in effect.

Since the above variations exist, it is recommended that the prices given in the equations developed on this program be used as maximum prices rather than use those suggested by the manufacturer (Reference 1).

Lime Recalcination

The fluidized bed recalcination process and equipment are very similar to that used for fluidized bed incineration of sewage sludge. It is recommended that a mathematical model be developed for the lime recalcination process, since phosphorous removal from sewage waste waters is fast becoming an important process.

TERMINOLOGY[a]

A1	=	Moles carbon in sludge considered based on sludge elemental composition
A2	=	Moles carbon in fuel for sludge considered
A3	=	Moles carbon in fuel and sludge considered
AF	=	Freeboard cross-sectional area, ft^2
AG	=	Grid cross-sectional area, ft^2
AIRCP	=	Heat content of combustion air @ 60°F for sludge and fuel considered (0°F base) Btu/#
AØ	=	Outside surface area of incinerator freeboard and bed sections, ft^2
APHC[b]	=	System air preheater cost for maximum allowable sizing, includes all reactors used, dollars as of Feb., 1968
APHS[b]	=	Air preheater size (maximum) for complete system, Btu/hr
B1	=	Moles H_2 in sludge considered
B2	=	Moles H_2 in fuel for sludge considered
B3	=	Moles H_2 in sludge and fuel considered
BAF	=	Air flow rate required for combustion of sludge and fuel at 4.0% excess $\emptyset_2$, # air/# sludge
C	=	Moles of $\emptyset_2$ in sludge considered
CAP	=	Capacity of incinerator system, # sludge/hr
CAPI	=	Capacity of each incinerator reactor used in system, # sludge/hr
CEF	=	Consulting Engineer's fee based on study field data capital costs, dollars as of Feb., 1968
CEFD	=	Consulting Engineer's fee based on Dorr curves for capital costs, dollars as of Feb., 1968
CF	=	Fuel cost for QFP for 1 year, current dollars, no preheat

---

a/ Note: # is an abbreviation used for pounds.

b/ APHCI and APHSI refer to a single incinerator system in a multiple incinerator installation

CFØ	=	Cost of fuel to operate, current dollars, not including startups, including heat loss from incinerator(s), $/yr (w/wo preheat)
CFP	=	Yearly cost of fuel replaced by air preheaters, current $/yr
CI	=	Installation cost based on study, $-Feb., 1968
CID	=	Installation cost based on Dorr curves, $-Feb., 1968
CL	=	Cost of operating labor per yr, current dollars, $/yr
CLM	=	Total cost of maintenance labor, current dollars, including overhead, $/yr
CLMA	=	Total cost of maintenance service labor, $/yr, current dollars, incl overhead
CLMR	=	Maintenance labor rate, current dollars, $/hr
CLMS	=	Maintenance service labor rate, current dollars, $/hr
CLR	=	Operating labor cost, current dollars, $/yr = $/8750 man hrs
CM	=	Cost of maintenance, current dollars, $/yr
CØ	=	Cost of operation, current dollars, $/yr
CØR	=	Cost of Reactor System less preheat based on field data, $-Feb., 1968
CØRD	=	Cost of Reactor System less preheat, Dorr curves, $-Feb., 1968
CP	=	Cost of electrical power, current dollars, $/yr
CPC2Ø	=	Heat content of $C\phi_2$ in exhaust @ 1400°F for sludge and fuel considered, Btu
CPH2Ø	=	Heat content of $H_2\phi$ in exhaust @ 1400°F for sludge and fuel considered, Btu
CPIN	=	Heat content of inerts @ 1400°F
CP2N	=	Heat content of N_2 in exhaust @ 1400°F, for sludge and fuel considered, Btu
CP2Ø	=	Heat content of O_2 in exhaust @ 1400°F, for sludge and fuel considered, Btu
CSL	=	Cost of sand loss, current dollars, $/yr
D	=	Moles of N_2 in sludge considered

DF	=	Diameter of freeboard, ft
DC	=	Diameter of grid, ft
DQ	=	Difference between makeup heat required to [illegible] and maximum air preheater heat available, Btu/hr
EC	=	Equipment cost including preheat(s) based on field data, dollars as of Feb., 1968
ECD	=	Equipment cost including preheater(s) based on [illegible], dollars as of Feb., 1968
EPC	=	Cost of 1 KW hour of electrical power, current dollars, $/KW hr
FBHP	=	Fluidizing blower HP for system
FBHPI	=	Fluidizing blower HP for each incinerator in system
FC	=	Cost of fuel, '68 $/1,000,000 Btu
FM	=	Mole multiplier for fuel
HE	=	Depth of expanded bed, ft
HF	=	Height of bed freeboard required, ft
HP	=	Height of plenum required, ft
HPI	=	Installed HP for system
HPII	=	Installed HP for each incinerator in system
NFP	=	Number of feel points per incinerator
ØHP	=	Operating HP for system
ØHPI	=	Operating HP for each incinerator in system
ØRH	=	Overall reactor height, ft
PAPH	=	Pounds ash generated per hour of operation, #/hr
PC1	=	Preheater maximum heat transfer rate to air from exhause products 1400°F inlet to 400°F exit, C_p = const., Btu/hr
PC2	=	Preheater maximum heat transfer rate to raise air temperature to 1000°F, Btu/hr
PC3	=	Allowable maximum heat transfer in air preheater limited by PC1 or PC2, Btu/hr

PCDS = Percent dry solids/100, # dry solids/# sludge

PCTY = Fraction of year, week or month to be operated, hrs operated/hrs yr (total hrs, not work hrs)

PDS = Pounds of dry solids per hour capacity of system, #DS/hr

PDSI = Pounds of dry solids per hour capacity of each incinerator in system, #DS/hr

PDSC = Pounds of dry solids under consideration from sludge elemental analysis considered, #

PH2Ø = Percent H_2O in sludge

PPH2Ø = Pounds H_2O under consideration from sludge elemental analysis considered, #

PS = Total pounds of sludge from sludge elemental analysis considered, #

PV = Plenum volume for each incinerator, ft^3

PVS = Percent volatile solids in sludge, %weight

PØVS = Pounds volatile solids under consideration from sludge elemental analysis, #

PVSH = Pounds volatile solids/hr capacity of system

PVT = Theoretical product volume, moles combustion products from system

PV4T = Moles combustion products @ 4% excess $Ø_2$ from system

QAIR = Input heat from combustion air @ 60°F, Btu/# sludge

QE = Heat content of combustion products and inerts leaving incinerator at 1400°F, Btu/# sludge

QF = Heat required from fuel to burn sludge adiabatically with no preheat at 1400°F and 4.0% excess $Ø_2$, Btu/# sludge

QFP = Heat required from fuel and preheat to burn sludge at 1400°F (QF + QPE), Btu/# sludge

QFU = Higher heat of combustion of fuel, Btu/# fuel

QL = Heat loss from combustion system by radiation and convection, which must be supplied by the heat of combustion, Btu/# sludge

QLE = Heat loss from pilot test combustion equipment by radiation and convection, Btu/# sludge

QLL = Calculated heat loss from AØ (neglecting radiation), Btu/hr

QPE = Heat supplied to preheated air during pilot test for fuel determination, Btu/# sludge, or heat content of air entering bec (0°F base)

QS = Total sludge heat input (higher heating value), Btu/# VS

QSL = Total sludge heat input (higher heating value), Btu/# sludge

SCP = Heat content of sludge 60°F (sludge considered in elemental analysis), Btu

SLR = Sand loss rate from bed, #/hr

SUM = Difference between heat content of exhause products 1400°F and heat input from sludge, fuel and air considered, Btu/# sludge

SUMQ = Total heat content of exhause products based on specific heats @ 1400°F, Btu/# sludge

TA = Contract ambient air temperature surrounding incinerator (if unspecified, use 60°F), °F

TCMØ = System annual maintenance and operating cost, current dollars

THCP = Total heat content of exhaust products @ 1400°F = SUMQ/PS, Btu/# sludge

THCPT = Total heat input to sludge from combustion and supply air and sludge, Btu/# sludge

TSC = Total system cost based on field data, dollars as of Feb., 1968

TSCD = Total system cost based on Dorr curves, dollars as of Feb., 1968

TW = Contract wall temperature of incinerator (use 200°F if unspecified), °F

VE = Volume of expanded sand bed required, ft^3

VS = Static volume of sand bed required, ft^3

XF = Moles N_2 in theoretical fuel and sludge air for sludge elements (composition considered)

Y = Excess moles $\emptyset_2$ required to reach 4% excess $\emptyset_2$

ZI = Design pounds of volatile solids each fluidized bed incinerator in the system handles, #VS/hr

ZII = Number of incinerators, in the system, required to handle the slude capacity at no more than 1500 # VS/hr per incinerator

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